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MASTER'S THESIS

Bluetooth Antennas Based on Stretchable Inks and Substrates: A Comparative Study between Different Antenna Structures

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ABSTRACT

Wearable technologies are expanding to consider different industries and systems such as healthcare solutions. Therefore, flexible, and stretchable electronics have gained huge attention recently since it made realizing a high performance, easy to use, comfortable, and durable electronics solutions possible. Wireless systems are also required to fit with wearable technologies, which include antennas. Therefore, a lot of research was focused on building stretchable and flexible antennas that are cost-effective, and easy to manufacture and integrate with existing solutions. One of the biggest challenges in stretchable antenna design is that antenna's radiation properties are dependent on the physical geometry of the antenna itself. Hence, utilizing existing 2D-based antennas that can maintain acceptable performance under stretching can be a challenging task.

In this thesis, I will investigate different antenna structures manufactured using commercially available inks EMS CI1036, ASAHI LS 411AW, and DUPONT PE874 as well as thermoplastic polyurethane substrates (TPU) Platilon U9122 and Platilon U073. I also studied the effect of stretching on the dipole, and meandered monopole antenna's performance and reported the simulation and measurement results when stretching the antennas up to 20% of its original length. I have also developed a novel algorithm for the placement and orientation process of the antenna on the TPU so that the effect of stretching on its performance is minimal. I have found that meandered monopole antenna can be a good candidate for stretchable applications due to its symmetrical response to stretching regardless of the stretching dimension, however, in other cases discussed in the thesis, I have shown that wire monopole or dipoles can be an excellent choice for stretchable applications in specific cases.

Key words: Stretchable Antenna, BLE Antenna, TPU-Based Antenna, meandered monopole antenna, meander monopole antenna, TPU, Platilon U9122, Platilon U073, flexible antenna, wearable antenna.

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FOREWORD

This thesis was carried out at VTT Oulu. The purpose of the thesis was to investigate the effect of stretching on TPU-based antennas, as well as suggesting design guidelines for utilizing 2D antennas for stretchable substrates. Also, I try to compare the performance of the antenna when it is based on different TPUs.

I would like to thank my direct team leader at VTT Oulu, Teemu Alajoki for his confidence, guidance, and the opportunity to investigate this topic as part of the Elastronics project. I would like also to thank RF Specialist Antti H. Tanskanen who have been always supporting and responding whenever possible.

Finally, I would like to thank my parents, wife, brothers, and my friends who I have met during my master's degree at Oulu University for their support during this journey.

Oulu, April, 16 2020

Belal Amin

LIST OF ABBREVIATIONS AND SYMBOLS

2D	Two-dimensional space
6G	Sixth Generation wireless communication systems
BLE	Bluetooth Low Energy
CNTs	Carbon Nanotubes
ESA	Electrically Small Antenna
NWs	Nanowires
PCB	Printed Circuit Board
TPU	Thermoplastic Polyurethane
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
Ag	Silver
c	Speed of light
C	Celsius
dB	Decibels
dBi	Decibels when indicating antenna gain
dBm	Decibels when indicating power ratio
F	Farad
f_0	Resonance Frequency
Hz	Hertz
m	Meter
mm	Millimeter
N	Newton
P_{rad}	Total radiated power
R	Radius
s	Second
U	Radiation intensity
W	Watt
z_{in}	Input Impedance
Z	Impedance
λ	Wavelength
µm	Micrometer
Ω	Ohm
ε	Permittivity
ε_r	Relative permittivity
$\tan\delta$	Loss Tangent
β	Reduction Factor

1 INTRODUCTION

1.1 Introduction

Wearable technologies have been expanding to many fields recently, including healthcare, sports, and entertainment. Therefore, it has gained an extensive amount of research attention in the past few years. The current research theme is more directed to flexible and stretchable wearable electronics, which have gained enormous attention in the scientific community as well as industrial partners. The goal of the current research efforts is to replace rigid electronics into more flexible, stretchable sheet-like electronics that can be washed, stretched, and even embedded as wearable technologies. Wireless modules that are responsible for near-field, as well as far-field data transmission, are a core module of most wearable technologies, especially in the era of 5G, where IoT and cloud-based systems will be a pillar of the new generation of technology. Wireless and RF systems have been considered for innovation that would allow for flexible as well as stretchable wireless modules and ease its integration into elastic electronics. An antenna is a core component of any wireless communication system; it is the component that is responsible for converting electricity into an electromagnetic wave that can be transmitted over the air and converting received electromagnetic waves into electricity to be proceed using electronic systems. Therefore, huge efforts have been given to produce a new class of stretchable and flexible antennas as well as its integration into flexible and stretchable circuits. New techniques and materials have been developed to cope with the advances in the wearable technologies that require a new generation of antennas. Also, lots of effort has been given to investigate and examine the usability and reliability of utilizing the conventional 2D printed antennas in the stretchable electronics domains.

This thesis focuses on examining the effect of stretching thermoplastic polyurethane (TPU) based antennas on the antenna performance and its radiation parameters. I also try to solve the associated challenges such as the assembly and the mechanical reliability of the antenna's feeding methods. Also, I will test the performance of stretchable Inks while utilizing different types of TPU-based stretchable substrate in RF application at around 2.45 GHz. Finally, I have proposed a novel algorithm that states the optimal positioning and orientation of the printed antenna on the TPU or any other stretchable substrate to make the antenna least affected by the stretching effect. The ability to utilize 2D TPU-based antennas and maintaining its performance while it is being stretched will propose important advances in wearable technologies and make it much lower in cost, more reliable, more stretchable, faster to manufacture and easier to assemble. The TPU-based stretchable antennas that are utilized in the scope of this thesis are manufactured, assembled using VTT labs. However, VTT Technical Research Center of Finland, Oulu office, does not have suitable antenna measurement equipment; hence, later in the thesis, I have shown a suitable testing setup that was built based on the available testing tools.

The structure of this thesis is as follows: Chapter 2 discusses the relevant theory that is essential in understanding the main problem that I am trying to solve as well as the solution and the measurement results. Chapter 3 deals with the TPU substrate and the process of preparing it. In addition, Chapter 3 also discusses the challenges and the steps for designing, manufacturing, and the assembly of the meandered monopole antenna. Chapter 4 list all simulation results for both dipole and meandered monopole antenna, as well as the measurement results of the meandered monopole antenna. Chapter 5 deals with many important topics; it starts by discussing adverse stretching models, especially, the main model of our concern in the scope of this thesis. Then section 5.1 discusses the simulation and the measurement results for the dipole and meandered monopole antennas and comment on the effect of stretching on both antennas when they are under different stretching models. Section 5.2 starts by introducing novel technical terms that I have introduced, which will be used later to set placement and orientation guidelines when placing the antenna on a TPU. Finally, Chapter 6 summarizes the thesis, going through the objectives, reviewing the main points in the thesis, and suggests future work.

1.2 Latest advances in stretchable and flexible antennas

In this section, I will discuss the literature and the latest advances in developing stretchable and flexible antennas for wearable applications. Wireless systems are core modules to allow wearable technologies to transmit and receive data to and from the outer world. Since antennas are essential modules in any wireless system, Therefore, developing stretchable antennas that can maintain its performance under large strain is becoming more essential. Hence, there has been a considerable amount of research efforts to develop new materials and technologies that would allow such antenna classes to exist. Before discussing the latest advances in stretchable antennas, there are different stretching models in real-life applications. One type of stretching can cause complete deformation of the relative dimensions of the antenna geometry, which can cause the antenna to perform in a very unexpected way, a hypothetical example for this case is a monopole antenna that can be stretched over its width to a great percentage so that it starts to look like a patch antenna rather a monopole, even though this is a very hypothetical example, it is used only to make this kind of stretching model more clear.

The other type of stretching model is when the stretching maintain the shape or relative values of the dimensions of the geometry of the antenna so that its radiation concepts still holds even after stretching, not necessarily performing the same, but at least it can still be analyzed with same theories as before stretching. This type of stretching model will be our main concern during our study in the scope of this thesis. I will refer to this model by simple stretching model in the rest of the thesis.

Considering the simple stretching model, there are different stretching behaviors that can occur, which are:

- Uniaxial Stretching: stretching that occurs over only one axis, such as x-axis or y-axis. Both axes should exist on the same plane of the 2D antenna under test.
- Biaxial Stretching: stretching that occurs over both axis x and y simultaneously. The stretching percentage can be with the same or different values for each direction.

In the scope of this thesis, uniaxial stretching is simulated for dipole and monopole antennas, and it was tested on meandered monopole antenna.

Initially, I will start with an introduction about the essential design considerations [1] when designing a stretchable antenna. The design considerations also represent the main challenges that need to be addressed when discussing a new antenna solution in general. Figure 1 summarizes the most important design considerations. Antenna efficiency is a major design goal when designing a new antenna, the measurement, and evaluation of a stretchable antenna’s efficiency is usually compared with the efficiency of the same antenna when designed on a rigid substrate. Another important parameter is the conductivity of the conductor that is utilized to build the antenna. The conductivity of the radiation element has a huge influence on the radiation efficiency of the antenna. The used substrate for the antenna application has a core role in determining the performance of many antenna structures such as the patch antenna, for stretchable antenna applications, the selected substrate need not only to provide big tensile strain but also to have a suitable dielectric constant that can make it suitable for stretchable applications, even under stretching. In addition, dielectric losses are an important parameter to consider when selecting a material that will be used as a substrate in a stretchable antenna application. Finally, the feeding method is an important step to carefully select when measuring antenna performance. In general, there are two possible feeding techniques for any antenna, direct and indirect feeding. Where direct means connecting different types of connectors such as SMA connector to feed the antenna or connecting it to a transmission line that will carry the input signal to the antenna. Indirect feeding such as coupled based feeding, where there is no physical connection between the antenna element and the feeding line, the indirect method is more preferable in stretchable applications since it decouples the effect of stretching on the feeding technique making the antenna more stable [1], as well as remove the physical connections which are usually considered as a weak connection point that is possible to disconnect under large tensile strain and cause the failure of the system. However, direct feeding techniques are more common in stretchable antenna designs because it is very easy to design and simpler to match.

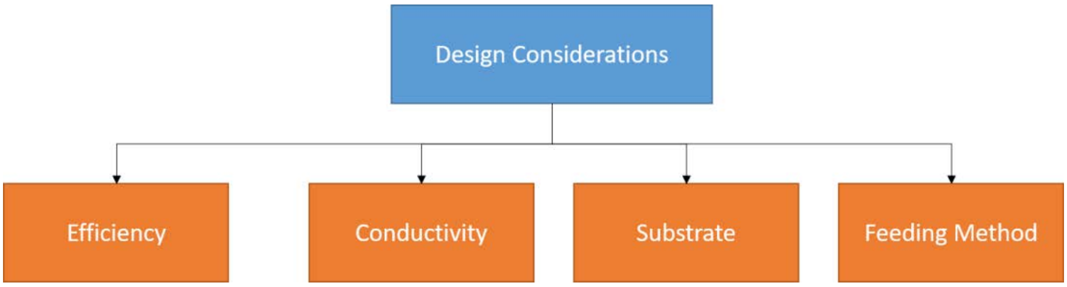


Figure 1. Antenna Design Considerations.

After discussing the design considerations and the challenges when designing a stretchable antenna, the available technologies and solutions for the stretchable antennas will be discussed. Initially, I will start by discussing the overview of the available technologies for designing a stretchable antenna, and then I will discuss each technology and give more details on each of them. In general, stretchable antennas consist of two main components, the substrate, and the radiating element. For conventional rigid antennas, depending on the frequency of operation, there are several available rigid substrates such as Rogers RT/Duroid laminates series 5870/5880 and RT Duroid 6000 series as well as FR4 while copper is usually used as the radiation conductor. On the other hand, when discussing stretchable and flexible antennas, the approaches are to replace the rigid substrate with a stretchable substrate such as TPUs [2], textile fabrics [3][4][5] or stretchable structures such as serpentine pattern [2][6][7], and 3D mechanically guided structures [8][9]. Flexible antennas are not necessarily stretchable if the goal is to design a flexible antenna, textile-based substrates as well as flexible elastomeric substrates can replace the conventional rigid substrates [10][11][3]. Once the rigid substrate is replaced with either a flexible or stretchable substrate that is suitable for the application under development, then for stretchable applications, the radiation elements of the antenna can also be replaced with stretchable counterparts. To replace the radiation element with a stretchable element, it is possible to use a stretchable material such as conductive textiles in the case of a textile-based antenna or trying to achieve a stretchable structure from conventional metals [8] such as silver which is utilized as stretchable ink in this thesis. An alternative approach to convert the radiation element to a stretchable element is to engineer a conductive element into a stretchable layout such as utilizing liquid metals embedded into a microfluidic network which can provide unlimited strain, or using conductive fillers embedded into composite elastomer such utilizing conductive nanowires [8][9]. Figure 2 summarizes all the possible approaches to achieve a fully or partially flexible/stretchable antenna, which is mentioned in this paragraph.

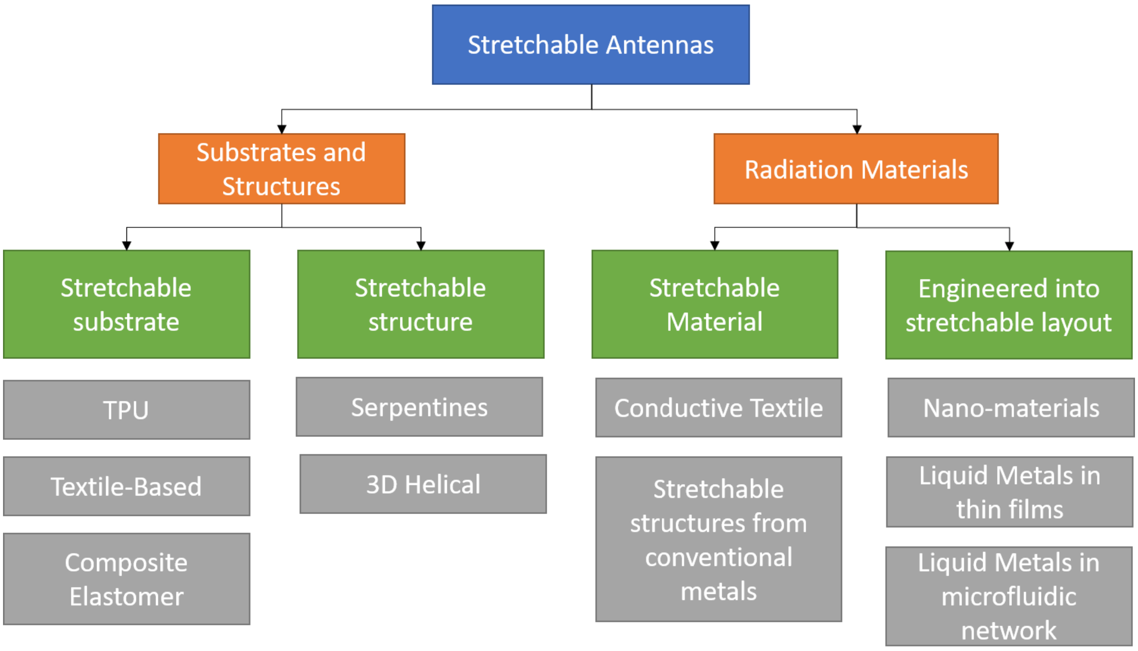


Figure 2. Overview of stretchable antenna technologies.

I have summarized the general roadmap in order to achieve a stretchable antenna, Figure 3 provides a more detailed map of the details of the available technologies. The first stretchable solution to discuss is the antennas based on liquid metal; it means that the radiation element of the antenna is replaced with a liquid metal that can flow in a microfluidic network of thin films that are embedded into a composite elastomer. This method provides good performance under big strain mainly because the liquid metal can provide stable performance under unlimited stretching since it is in a liquid state and can easily flow in stretched elastomer, while the elastomer substrate is what controllers and limit the mechanical performance during stretching. Gallium-based liquid metals are commonly used in this type of antenna especially in healthcare-related solutions due to its nontoxicity and good conductivity ($3.46 \times 10^6\ S/m$) [12]. There have been many examples of antennas that are built utilizing liquid metal as the main radiation element, such as dipole antenna [13][14][15], patch antenna [16][17][18] and planar inverted cone antenna [19].

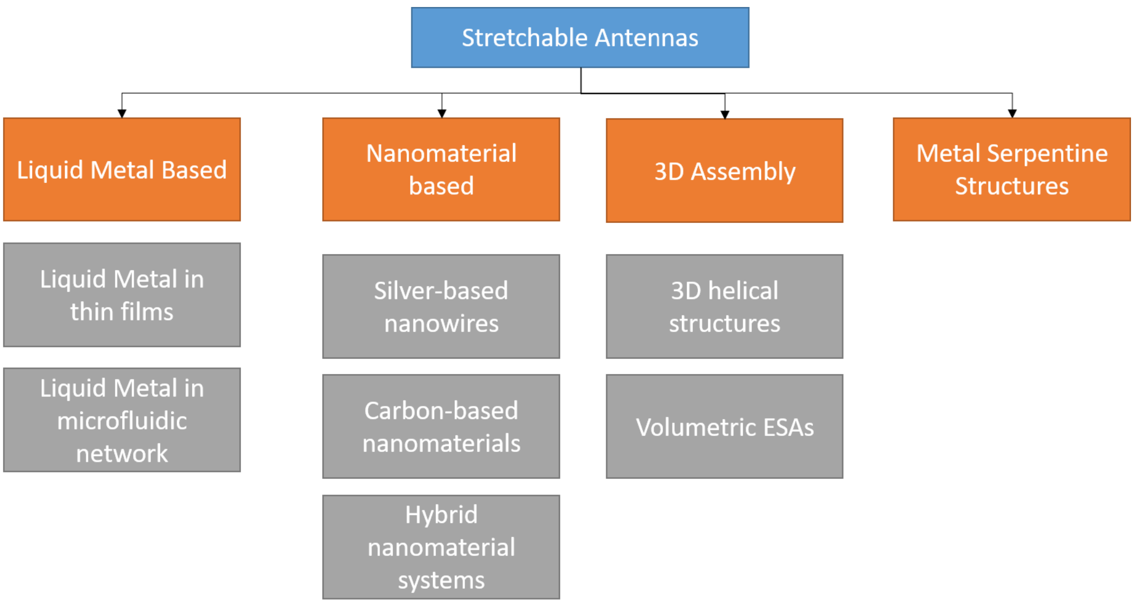


Figure 3. Stretchable Antenna Available Solutions.

The integration of nanomaterials that are used as the radiation element in antennas has gained attention in the antenna community. Metal nanowires (NWs), as well as carbon nanotubes (CNTs), can support flexibility as well as stretchability. There have been examples of antennas based on nanomaterials such as patch antennas [20], dipole [21], and monopole [22]. Hybrid nanomaterials consisting of (silver-based nanowires) AgNWs-graphene antennas can yield a transparent and highly stretchable antenna that can stand stretching up to 20% [9].

So far, I have covered stretchable antenna systems where the radiating material is replaced with various solutions to allow stretchable radiating elements. As mentioned earlier, to convert the conventional rigid antenna systems, it is required to replace the rigid substrate to either stretchable counterpart or utilize a stretchable structure that can provide stretching behavior by nature. Possible stretchable structures are serpentine based, and 3D mechanically guided structures mentioned in Figure 2. Serpentine-based structures usually utilize radiation material from conventional metals. Serpentine, also called meandered shape structures, can easily be implemented by converting straight lines into meander shape lines and transfer this pattern onto a stretchable elastomer such as TPU. A demonstrated example, such as meandered dipole antenna on TPU [23], has been reported. The strategy for converting more complex layouts than simple lines into stretchable serpentine mesh layouts has been discussed in detail in [7].

Finally, 3D-based antennas have shown interesting results when it comes to the stable performance of antennas under stretching [9]. 3D helical structures formed by integrating complex 3D microstructures on an elastomeric substrate have shown better mechanical stability and more stretchability over its 2D counterparts [24]. Mechanically guided 3D assembly have also shown promising solutions by building volumetric Electrically Small Antennas ESAs, where electrically small antennas are defined so that the electrical size of the antenna is less than 0.5 as defined by ka, where k is the free space wavenumber, and a is the radius of the smallest sphere that circumscribes the antenna [25]. ESAs has great advantages since it can be extremely small yet can provide acceptable performance under stretching [9].

2 THEORY

In this chapter, I will explain the most relevant antenna theory that is required to understand the content of the thesis. Such as the essential antenna parameters as well as the different antenna structures that are relevant to this thesis. Most of the equations and theories mentioned in this chapter will be based on [26].

2.1 Antenna parameters

In order to design an antenna, I will explain some essential parameters that characterize an antenna performance. In the following subsections, I will explain all relevant theories that are essential prerequisites to understand how antennas work, such as field regions, radiation patterns, directivity, antenna efficiency.

The first concept to discuss is field regions. Field regions around the antenna could be divided into three main regions, which are reactive near-field, radiating near-field (Fresnel), and far-field (Franhoufer). Figure 4 shows the field regions around the antenna and the shape of the radiated signal in each region.

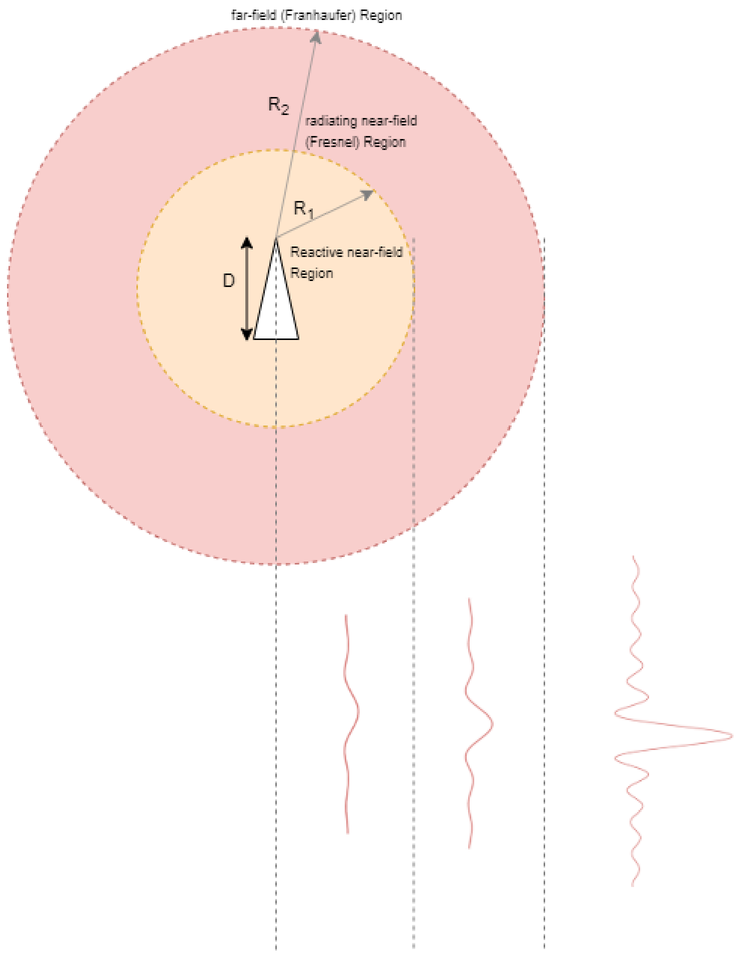


Figure 4. Shows different regions around the antenna and the amplitude pattern of the transmitted signal in each region from reactive near field to far-field.

The reactive near field is the field that is immediately next to the antenna. It is defined as

$$R_1 = 0.62\sqrt{\frac{D^3}{\lambda}}, \tag{1}$$

where D is the largest dimension of the antenna, and λ is the wavelength of the signal in this region. The reactive fields are predominant in this region.

Radiating near-field region is the region that is between the Reactive Near-Field and the Far-Field. Radiating fields are predominant in this region, and the field pattern is a function of the distance of the antenna. It is defined as

$$0.62\sqrt{\frac{D^3}{\lambda}} < R_2 < \frac{2D^2}{\lambda} \tag{2}$$

The Far-Field region is the region where the field pattern is not a function of the distance from the antenna. It is the most important region, as this is where most of the antennas are meant to work and where most of the measurements are done. It is defined as:

$$R_3 < \frac{2D^2}{\lambda}, \tag{3}$$

where R_3 is the distance from the antenna. Also, it is worth noting that usually $R_3 \gg D, R_3 \gg \lambda$.

The second parameter to discuss is the radiation pattern. The radiation pattern is a representation of the radiation intensity of the antenna as a function of direction, typically refers to the far-field pattern. It can be represented on a 2D polar chart, as seen in Figure 5 or 3D chart, as seen in Figure 6. The radiation pattern is a reciprocal parameter, which means, the same radiation pattern is expected whether the antenna is used as a receiving or transmitting antenna. According to the spherical coordinate system, theta is the angle measured off the z-axis, and phi is the angle measured counterclockwise off the x-axis.

There are two types of antennas

1. Omnidirectional, which means that the antenna does not prefer a specific direction to another, it basically transmits or receives all power equally in all directions in a specific plane, while varying power with respect to angle to that specific plane. A close example of an omnidirectional antenna in one plane is the radio antenna, which is usually installed on the car roof.
2. Directional, which means that the radiation pattern is focused towards a specific direction and not symmetrical, this is useful when it is needed to transmit the signal in a specific direction or receive from a specific direction. A popular example of this directional antenna is a dish antenna, which is used for satellite communication.

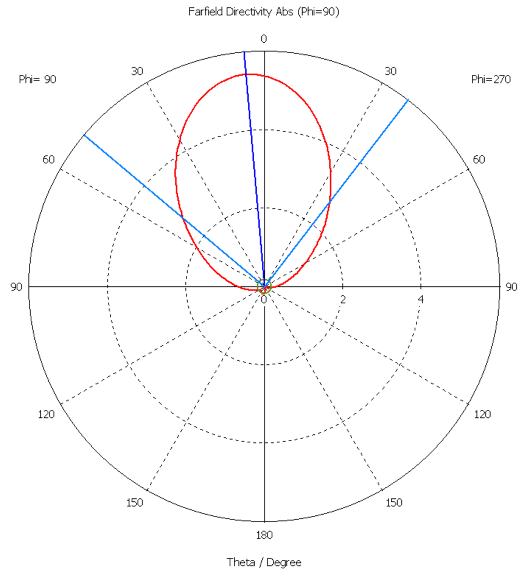


Figure 5. 2D Polar plot that represents the radiation pattern of a microstrip antenna.

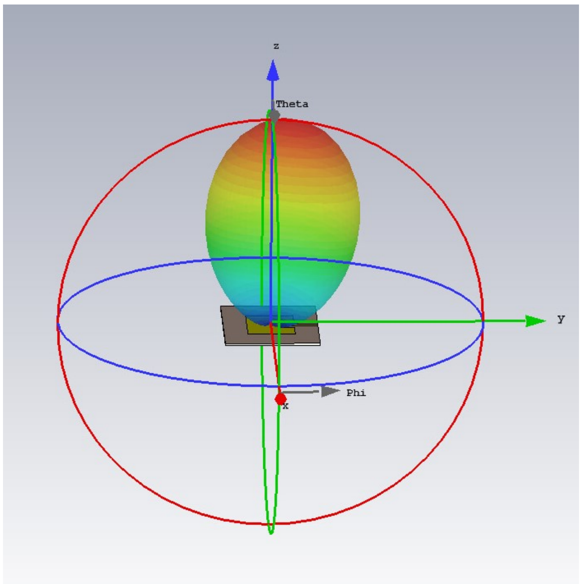


Figure 6. 3D Plot that represents the radiation pattern in 3D of a microstrip antenna.

The third parameter to discuss is directivity. Directivity is the ratio of the radiation intensity in a specific direction to the averaged radiation intensity over all directions.

For instance, a solution that is more probable to receive or transmit from/to a specific direction, then it needs a directive antenna, which means an antenna that has most of its power received or transmitted towards a specific direction. On the other hand, if the antenna to be integrated into a solution that is expected to have symmetrical behavior for all directions (e.g., cell phone), then a low directivity antenna will be more suitable.

Directivity can be calculated as

$$D = \frac{4\pi U}{P_{rad}}, \tag{4}$$

where U is radiation intensity (W/unit solid angle), P_{rad} is total radiated power (W).
Table 1 represents typical directivity for common antenna types

Table 1. Typical directivity for common antenna types [27]

Antenna Type	Typical Directivity (dBi)
Short Dipole Antenna	1.76
Half-wave Dipole Antenna	2.15
Patch Antenna	5-8
Horn Antenna	10-20
Dish Antenna	10-40

The last antenna parameter to discuss is antenna efficiency. Antenna efficiency is one of the most important antenna parameters, and it is defined as the ratio between the power that is delivered to the antenna input to the power radiated from the antenna. Antenna efficiency could be divided into two main useful terms as the following:
Radiation efficiency: does not consider mismatch efficiency.

- Total efficiency: considers all efficiency.
- The total efficiency can be modeled by the following equation

$$e_0 = e_r e_c e_d, \tag{5}$$

where e_r is the reflection efficiency, $e_c e_d$ are the conduction efficiency and dielectric efficiency, since it's hard to separate them, usually, they are measured and represented together and used as a single term e_{cd} which is the radiation efficiency.

Antenna efficiency shows how much power is utilized rather than converted to heat or reflected back to the excitation port. For instance, if an antenna is fed with 10 dBm, and it radiated only 8 dBm to the air, hence, it is said that the efficiency of the antenna is -2 dB.

The cause for that loss could be for several reasons, it could be lost as heat, or lost due to the conduction or dielectric losses of the substrate or the conductive ink, or it could be due to impedance mismatch which in turns caused a portion of the signal's power to be reflected back.

2.2 Substrate parameters

In this section, I will discuss important substrate parameters that are relevant to antenna performance analysis. The first parameter to discuss, which is related to the substrate of the antenna, is permittivity. Static Permittivity is a measure of the ability of the dielectric material to store the electric field in the form of polarization when an electric field is applied to that material. It is usually referred to it as the Greek letter ε, and its unit is Farad per meter.

Permittivity is also called dielectric constant. Vacuum permittivity is the smallest permittivity to our knowledge, and it is represented as ε_o it approximately equals to $8.85 \times 10 - 12\ F/m$.

Permittivity is quite a basic topic related to electromagnetic theory [29], however for an Antenna topic, the most important thing to know about it is that permittivity represents capacitance measured when applying an electric field on the material, hence it affects the speed of the propagation of the signal through the substrate being used which results into different electrical wavelength of the signal than it is in air.

Usually, in antenna field, its referred to materials by a dimensionless property which is Dielectric Constant or it is also called relative permittivity ε_r, simply it's the ratio between the permittivity of the substrate in hand to the permittivity of vacuum/air (they are almost equal, and the difference is negligible) and calculated as

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \tag{6}$$

Sometimes such as in microstrip patch antenna, the signal travels through 2 different mediums, air, and the substrate. A new term called effective dielectric constant is then defined to accommodate such a case. The higher the permittivity, the better the material is maintaining or storing an electric field applied to it, the lower it is, the less efficient it is maintaining an electric field applied to it.

The last substrate related parameter to discuss is dielectric losses. Dielectric Losses is a representation of the losses caused by the dielectric material due to the dissipation of electromagnetic energy. It could be presented using the Loss Tangent $\tan \delta$.

2.3 Antenna types

In this section, I will explain the antenna structures that are relevant to the thesis work. I will give a short introduction about each type, then explain the structure, Analysis theory, and the design guidelines for antennas that are simulated and measured.

2.3.1 Dipole antenna

The dipole antenna is one of the earliest types of antennas known so far, and its radiation principle is extremely simple and straight forward. In this section, I will try to give a very short introduction about the radiation principle of the dipole and how it works. In order to visualize the ”evolution” of the dipole antenna, I have shown in Figure 7 how the reader can have a mental image in order to easily understand the radiation principle of the dipole antenna.

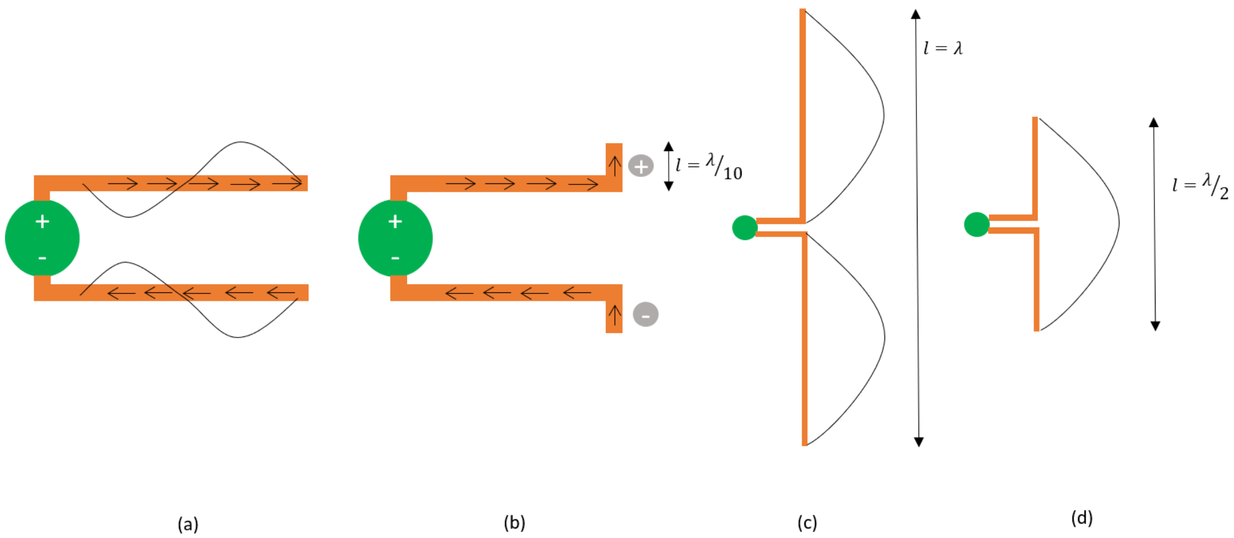


Figure 7. Dipole antenna, a) Simple transmission line, b) Short-dipole antenna, c) Full-wavelength dipole, d) Half-wavelength dipole

Considering Figure 7 (a), it is a simple open-circuited transmission line, where each section of the transmission line is one wavelength. In that case, the current distribution will be as shown in Figure 7 (a). In this scenario, there is no radiation, since there is no kind charge building that can allow radiation. In order to make it radiate even with a very small directivity, first start bending the edges up and down as shown in Figure 7 (b), In this case, charges will start adding up in phase at the edges, where the current is flowing in the same direction which causes radiation. In this case, it is called a short dipole antenna. Short dipoles have a small directivity that is around 1.76 dB. Since the short dipole is as the name suggests, it is short, there is a little amount of current flowing and adding up in phase, in order to have a better performing antenna, how about increasing $l = \lambda$. Even though this will give much more amount of current flowing up and down, yet, this is not going to radiate and will be considered as a very poor radiator. The reason for that is simple, as shown in Figure 7 (c), the current in the middle for both segments, is theoretically zero. Therefore, the Impedance is almost infinity, hence, it is almost impossible to deliver power to the antenna. So the solution now is to try to make the current at the feeding point not equal to zero, and this is where the half-wavelength dipole is considered a solution as shown in Figure 7 (d), with this configuration, the current is adding up while the impedance is not infinite, the input impedance of very thin half-wavelength dipole is given by

$$z_{in} = 73 + j42.5. \tag{7}$$

2.3.2 Meandered shape monopole antenna

Meandered monopole antenna, also known as meander line antenna, is a new class of resonant antenna that was initially introduced by Rashed and Tai [30]. It was designed specifically to be compact in size as compared to conventional monopole antennas that have the same resonance frequency, when mentioning compact in size I mean up to 0.25λ [31]. The meandered monopole antenna is realized by continuously folding a wire or a monopole antenna so that it looks as shown in Figure 8. The amount of reduction in size for a meandered monopole antenna of length L that has a resonance frequency f_o is equal to $\beta = \frac{L}{l}$ where β is called the reduction factor [30], and l is the length of a conventional monopole antenna that has the same resonance frequency f_o. β also depends on the width of the trace in case that the antenna trace has uniformal width, or the width of the rectangular loop as a general rule, also it depends on the number of sections N per wavelength.

Even though the meandered monopole antenna is considered very compact size compared to the conventional monopole antenna, this comes with a cost of reduced efficiency, smaller bandwidth as well as less radiation resistance [32]. The meandered monopole antenna analysis is discussed in more detail in [30] [33].

In the configuration shown in Figure 8, the antenna feedline is assumed to be coaxial-based that feeds the antenna from the bottom layer to the upper layer. The meandered monopole antenna can be assumed as LC resonant circuit where the vertical lines that are annotated as leg act as a capacitor and the horizontal segments act as an inductor as discussed in [34].

I have provided a Matlab code that will help to design the PCB layout of the meandered monopole antenna that is shown in Figure 8 in Appendix 1 below. It requires some experimentation in order to find the exact physical dimensions that can give the best antenna performance for a meandered monopole antenna. However, Table 2 shows a general overview of the effect of each dimension of the meandered monopole antenna on the antenna resonance frequency and its bandwidth.

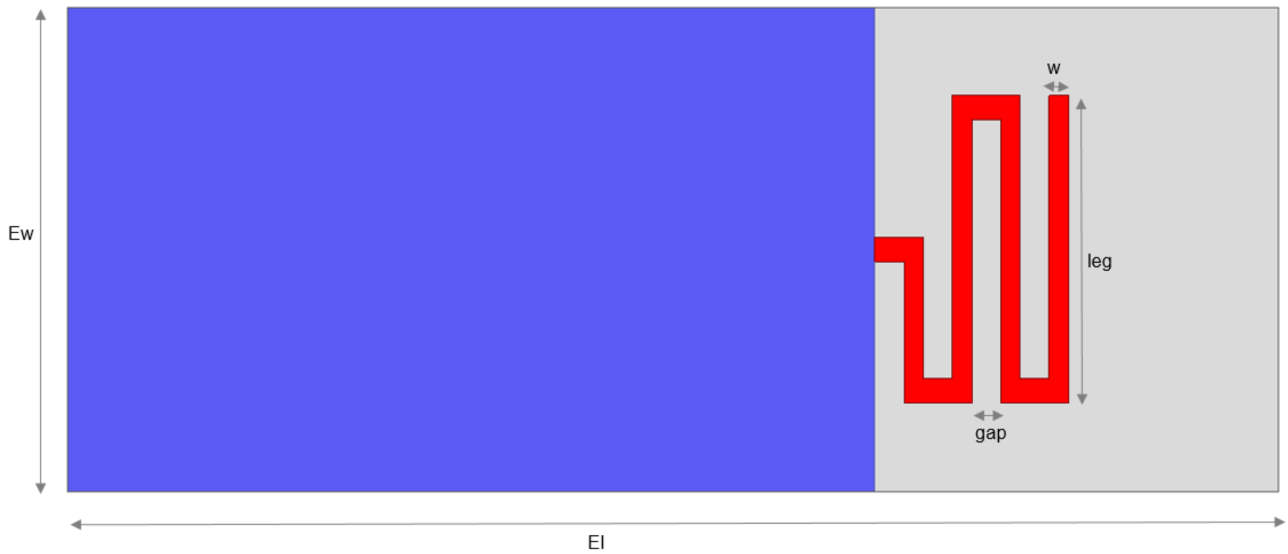


Figure 8. Meandered monopole antenna.

Table 2. Effect of Meandered Monopole Antenna's dimensions on the Resonance Frequency and Bandwidth [35]

Antenna Dimension	Change	Parameter	Effect
W	Increase	Resonance Frequency	Increase
		Bandwidth	Becomes Wider
	Decrease	Resonance Frequency	Decreases
		Bandwidth	Becomes Narrow
Leg	Increase	Resonance Frequency	Decreases
		Bandwidth	Becomes Narrow
	Decrease	Resonance Frequency	Increase
		Bandwidth	Becomes Wide
Gap	Increase	Resonance Frequency	Decrease
		Bandwidth	Becomes Narrow
	Decrease	Resonance Frequency	Increase
		Bandwidth	Becomes Wide
El	Increase	Resonance Frequency	Decrease
		Bandwidth	Becomes Wide
	Decrease	Resonance Frequency	Increase
		Bandwidth	Becomes Narrow

2.3.3 Microstrip rectangular patch antenna

Microstrip antenna is one of the most popular antennas nowadays due to its ease of manufacturing, printed on PCB, cheap, and easy to analyze. This section will cover the most important and required knowledge about the microstrip antenna, also called a patch antenna.

Microstrip Patch Antenna is quite simple in structure, which makes it very interesting and common antenna to be utilized whenever possible. It can take various geometric shapes, such as square, rectangular, circular, dipole, as seen in Figure 9. square, rectangular, and circular are most common due to the ease of their analysis and fabrication.

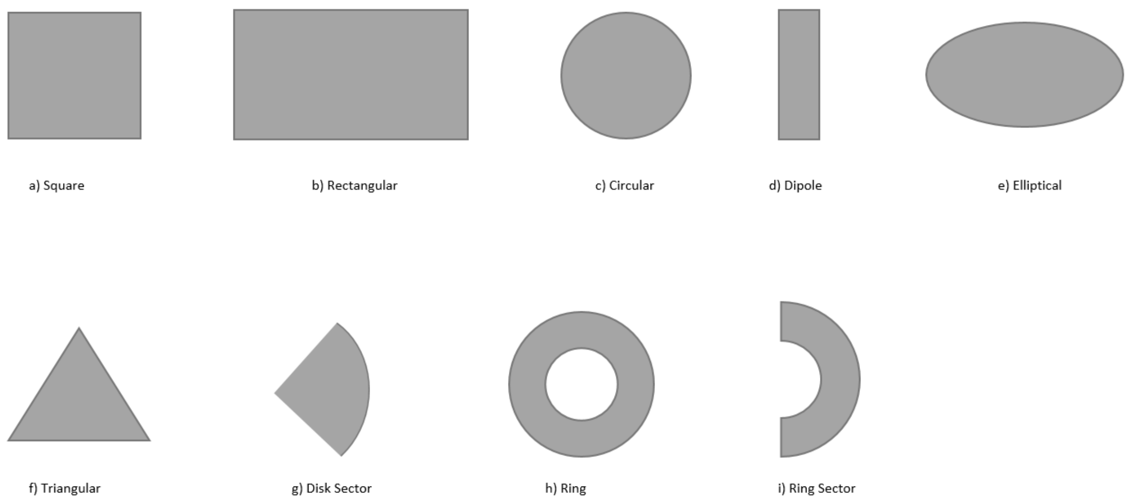
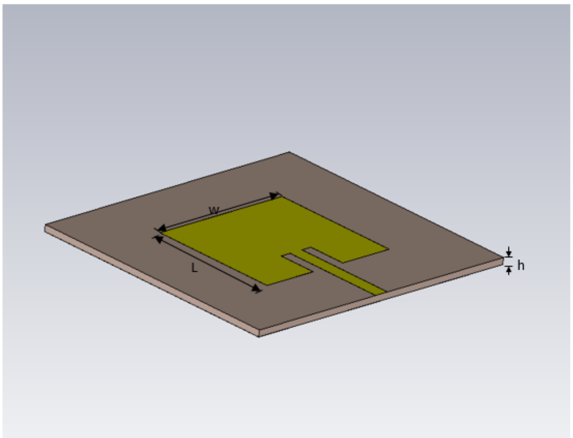
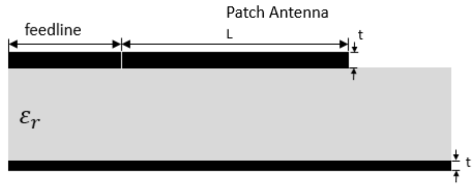


Figure 9. Patch antenna possible structures.



(a) Microstrip Antenna



(b) Side view

Figure 10. Microstrip rectangular patch antenna.

The rectangular patch antenna is easy to analyze; therefore, it was chosen as a choice to implement and analyze in the scope of this thesis. First, to understand the feeding methods for a patch antenna, to there are multiple feeding methods feed a rectangular microstrip patch antenna, The most common ones are, microstrip line, coaxial probe, aperture coupling and proximity coupling [26]. In this thesis, the microstrip line is used to feed the microstrip patch antenna, because it is very easy to match by controlling the inset position, easy to fabricate and simple to model. The microstrip feeding line can be shown in Figure 10 (a). Usually, the microstrip line is very small in width in comparison with the width of the patch itself.

There are multiple ways to analyze the patch antenna, such as transmission line, cavity, and full-wave [26]. I have considered Transmission-line Model to explain the analysis of the patch antenna since it is easy to analyze and model while giving good insights on the antenna performance, yet the transmission line model is the least accurate model.

The main idea behind the radiation of the patch antenna shown in Figure 11 and Figure 10, is called Fringing, I will try to make it as simple and as easy to understand as possible. Considering Figure 11, the current distribution is zero at the end of the patch, because it is an open-end, and maximum in the middle, while theoretically zero at the beginning, but in practical life, it is not actual zero – and this is the reason why the patch antenna has a very high input impedance that is almost equal to 400 Ω - at the same time, the voltage is out of phase with the current. Therefore, the voltage will be maximum at the end of the patch, zero at exactly the middle, this is where the current is max, and minimum at the beginning of the patch. This causes the fringing effect. The fringing fields add up in phase, and this is the main reason why the patch radiates.

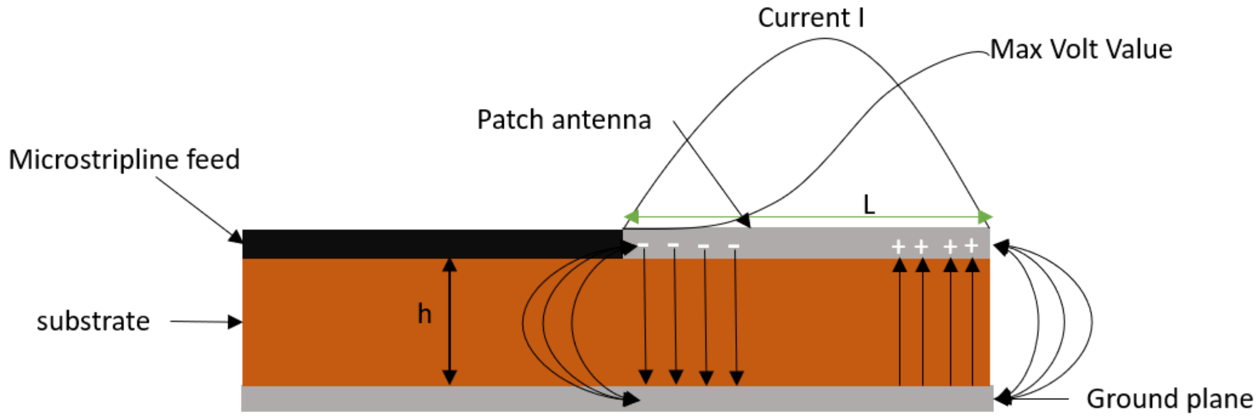


Figure 11. Sideview of the patch antenna and fringing effect.

Due to the fringing effect, the antenna length looks electrically longer than what is. Hence, the resonance frequency would be less than what is initially calculated as

$$f_0 = \frac{c}{2L\sqrt{\varepsilon_r}} \tag{8}$$

In order to calculate the extension of the length as well as the width and the other required parameters that are required for the patch antenna design, I have presented Matlab code in Appendix 2 below.

3 DESIGN AND MANUFACTURING

This chapter will contain the details of the TPUs and inks that are used as a stretchable substrate for the antennas. I will also discuss the process details of preparing the TPU to be utilized as a substrate, as well as discussing the antenna layout design and the assembly process.

I have used multiple substrates as well as different Inks to build the antenna structures, which are simulated and discussed in the following chapters. Two thermoplastic polyurethane substrates and three Inks are used in this thesis. The substrates are Polyurethane U073 [36] and Platilon ID9122 [37] below. The pre-treatment of the TPU can affect the substrate's mechanical performance [38]. Inks also can be proceed using different parameters such as layer thickness, drying duration, silver content, etc. different parameters will result in different properties of the final sample in terms of resistivity, conductivity, and mechanical reliability. Hence, I will report different parameters used to manufacture the antennas which are used in this thesis. Inks that are used in this are DUPONT PE874 [39], ASAHI LS411AW [40], CI-1036 [41].

As far as I know, the TPU substrates that are used in the scope of this thesis have not been characterized for RF applications. Hence, I will measure the relative dielectric constant (permittivity) and the dielectric losses of the substrates. There are various ways to measure the permittivity and the dielectric losses of the substrate. Since this thesis is more focused on the stretching effect on antenna performance using the provided substrates and Inks, I will only report important parameters that can affect our antenna design only, such as the relative permittivity since it will directly affect the design of the antenna for a specific frequency. Even though the dielectric loss is a crucial material parameter in RF applications, since it will have a huge effect in understanding the efficiency components of our antenna, it will not be investigated in detail in the scope of this thesis. However, basic measurements will be done to provide some insights. The TPU characterization setup is presented in Figure 12. Characterization results are presented in Table 3. Due to the limitation in the measurement technologies that were available, I was able to conduct the measurements up to 1 GHz only, however, it is well expected that the behavior will be consistent up to 3 GHz.

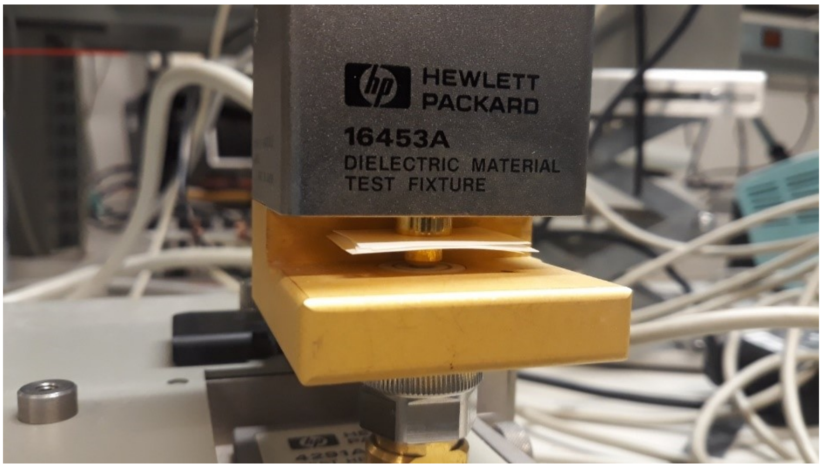


Figure 12. TPU characterization setup.

Table 3. TPU characterization

TPU_ID9211			TPU_U073		
$t = 2 * 150$ µm; $4 * 150$ µm			$t = 4 * 100$ µm		
f / MHz	ε_r	$tan(\delta)$	f / MHz	ε_r	$tan(\delta)$
10	4.09	0.07	10	4.36	0.08
100	3.67	0.08	100	3.84	0.09

200	3.54	0.09	200	3.67	0.10
300	3.43	0.10	300	3.55	0.11
400	3.35	0.11	400	3.45	0.12
500	3.29	0.11	500	3.39	0.12
600	3.24	0.12	600	3.33	0.12
700	3.19	0.12	700	3.27	0.12
800	3.15	0.12	800	3.23	0.12
900	3.12	0.11	900	3.20	0.12
1000	3.09	0.11	1000	3.16	0.12

3.1 Antenna design and manufacturing process

In this thesis, I have simulated three antennas, dipole antenna, meandered monopole antenna, and microstrip patch antenna. However, dipole antenna was simulated, and its simulation results were reported, but it wasn't manufactured due to its feeding complexity, the patch antenna was also simulated, but the simulation results weren't reported in this thesis due to its very poor performance due to many reasons mentioned in the next chapter. The meandered monopole antenna is simulated, reported, manufactured, and measured. Hence, in this chapter, I will report the PCB layout design steps, manufacturing process as well as the assembly steps, and the challenges I have faced while assembling the antenna, SMA, and the TPU.

In the first step, I have designed the PCB layout for the meandered monopole antenna using Altium designer software. Since I utilize two different TPUs, U073 and ID9211, that have different dielectric properties, hence, the physical dimensions of the meandered monopole antenna are different, the physical dimensions of the antenna for each substrate are mentioned in Table 4. The physical dimensions of the meandered monopole antenna for this given frequency is directly taken from [35] and is not manually calculated.

Table 4. Physical dimensions for meandered monopole antenna PCB layout for different TPUs

parameter	**TPU_U073**	**TPU_ID9211**
E_l	50mm	50mm
E_w	20mm	20mm
gap	1.2mm	1.2mm
leg	12.05mm	11.75mm
w	0.8mm	0.8mm

It is useful to mention that the available circuit design tools and PCB layout design tools are not necessary to produce the production files needed to manufacture the antenna on TPU because the production machines used to prepare the final sample on top of the TPU has its own process that is different in its requirement from conventional PCB printing requirement, these steps are discussed later in this chapter. The final layout of the meandered monopole antenna is shown in Figure 13, and the design consists of four antennas, two antennas per row. For a faster manufacturing process, I have combined both antennas TPU_U073-based antenna and TPU_ID9211-based antenna in a single layout. The antenna itself is drawn in red and in the top layer, and the ground plane is drawn in blue and in the bottom layer, where the brown dot is a hole or via from bottom to the upper layer, which is needed for the SMA connector which is used to feed the antenna. As seen in Figure 13 at the top, there is a black box that has two vertically aligned green dots inside. The black box is not part of the design; it is only for annotation purposes to annotate that these two dots are extremely important in our case, and they are called alignment dots, the purpose for the alignment dots will be mentioned while explaining the manufacturing process of the antenna.

In order to prepare the layout for manufacturing, the first step is to print each layer on a different transparent film, as seen in Figure 14 and Figure 15. The transparent films are printed using standard printing machines. Once the transparent films are ready, the alignment dots are used to align both transparent films to make sure that our designs are perfectly aligned, as seen in Figure 16. It is also worth mentioning that the alignment dots and the green border that are shown in Figure 13 are used in the TPU printing machine itself in order to assure accurate printing and perfect alignment when the antenna is printed on top and bottom sides of the TPU.

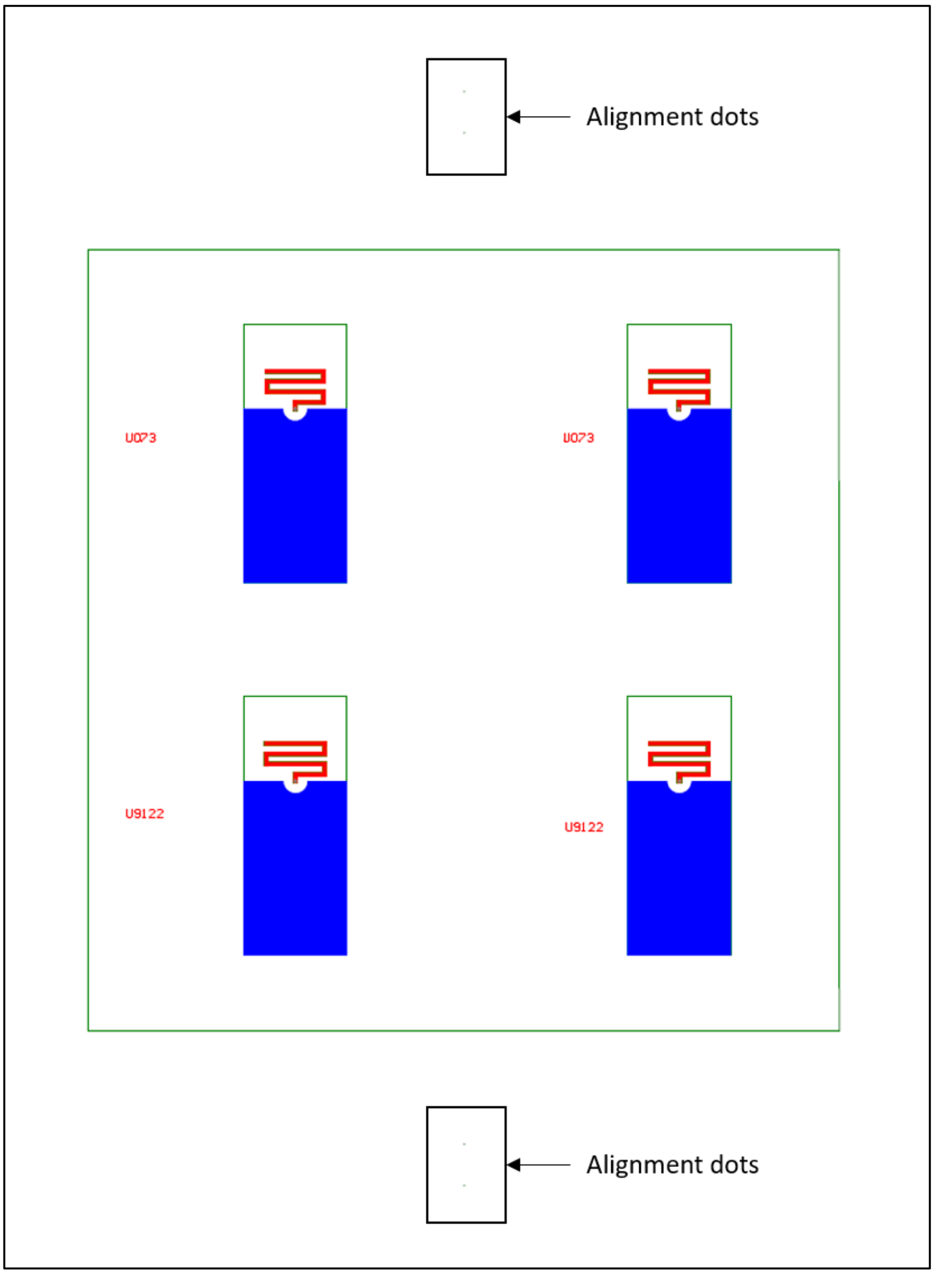


Figure 13. Final PCB layout for meandered monopole antenna.

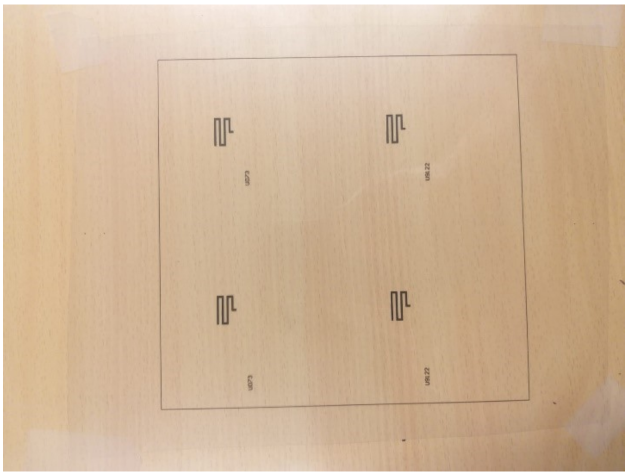


Figure 14. Meandered monopole antenna top layer printed on transparent film.

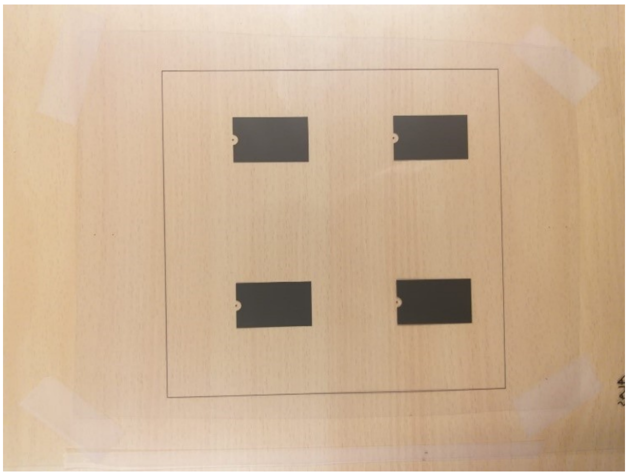


Figure 15. Meandered monopole antenna bottom layer printed on transparent film.

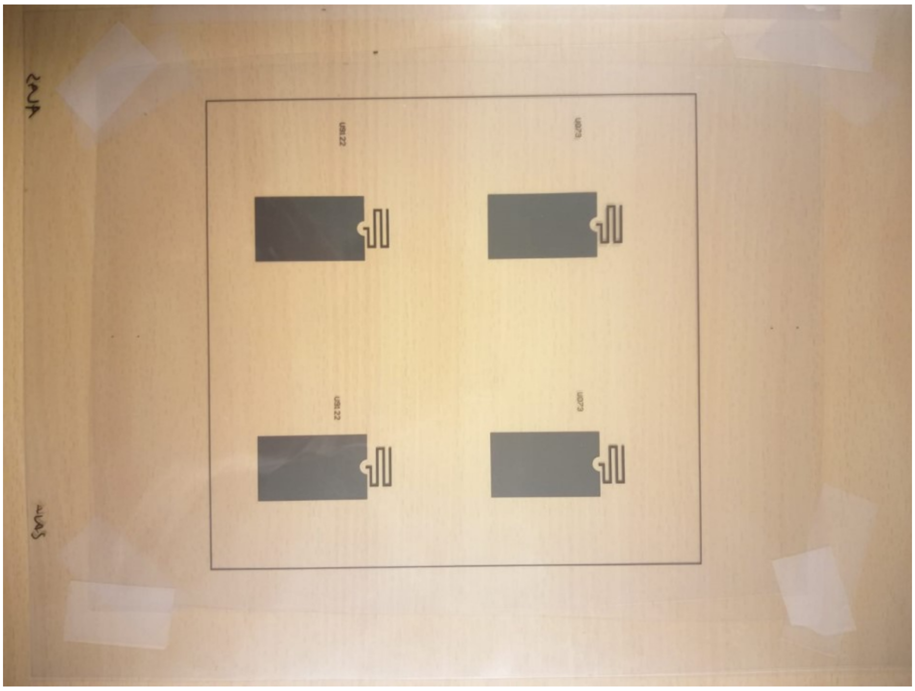


Figure 16. Top and Bottom layer of meandered monopole antenna printed on transparent film and aligned.

Now, once the transparent films are ready and aligned, it is ready for the manufacturing process. For the manufacturing, two screens were used, one screen for each layer, top layer, and bottom layer. I have printed three samples for each TPU, where each sample utilizes three different conductive inks, which are LS411AW, CI-1036, and DP PE874. Ushio MP-8200 Multi Punch Machine was used for punching the TPUs to create the holes that will be used to feed the antenna with the input signal, which is 1mm in diameter. Ekra XH-STS machine is used for printing on the TPU with printing parameters as following:

- Printing parameters: DownStop: $200\mu\mathrm{m}$, SnapOff: $1{,}2\mathrm{mm}$, Pressure $70N$, Speed $40\mathrm{mm}/s$.
- Screens: Steel 325 mesh, wire $28\mu\mathrm{m}$, emulsion $15\mu\mathrm{m}$.
- Printing Rakel: Rubber, diamond, D70.
- The thickness of the dried Ag prints:

- LS411AW: ~30µ
- CI-1036: ~17µm
- DP PE874: ~10µm

Initially, mylar (carrier foil) is taken off from the TPU_U073 and TPU_ID9211, and then it is heated at the furnace at $120°C/60\mathrm{min}$. Then another new mylar was laminated on the other side of the TPUs. Next, the 1mm holes were marked on the TPU at the alignment marks. Once the holes are marked, the antenna traces are printed on the top side of the TPUs then it is dried at $70°\mathrm{C}$. When the top side is dried, it is laminated with mylars, and the mylar that was previously installed on the bottom side is then removed. The next step is to print the ground plane on the bottom side of the TPU and leave it to dry at $70°\mathrm{C}$. Now, the mylar is removed from the top layer, and the TPU is unlaminated and left for drying at $120°\mathrm{C}/30\mathrm{min}$. Finally, 1mm holes are punched at its assigned location. The reason for laminating both sides of the TPU, especially TPU_U073, is that it shrinks and stretches a lot during the drying in the furnace if it doesn't have a mylar on it, hence, mylar was used on both layers when drying it to ensure accurate and reliable performance. However, TPU_ID9211 might not necessarily need this mylar. The final manufactured meandered monopole antenna is shown in Figure 17.

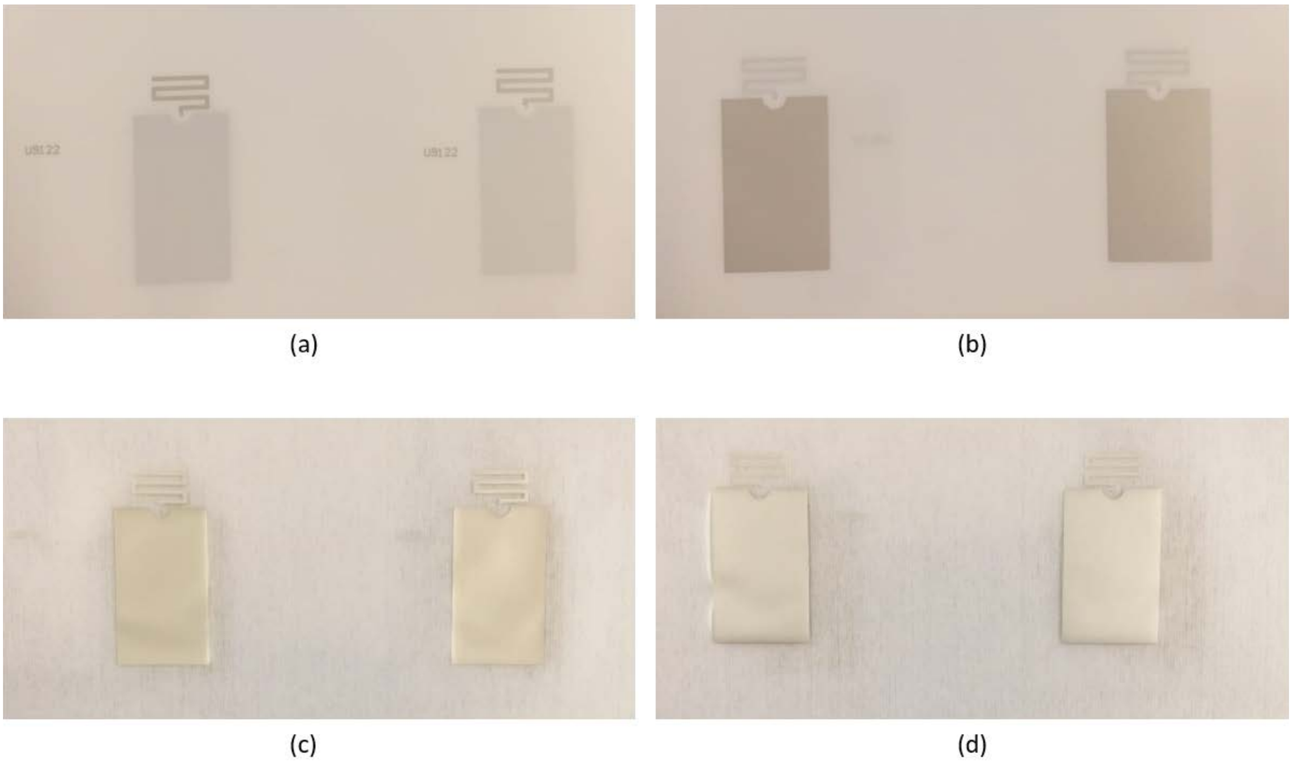


Figure 17. Manufactured meandered monopole antenna, a) Top layer on TPU_ID9211, b) Bottom layer on TPU_ID9211, c) Top layer on TPU_U073, d) Bottom layer on TPU_U073.

Now, the Meandered Antenna is successfully manufactured. The final step in order to prepare the antenna for measurement is to install the SMA connector, which will be used to feed the antenna from the bottom layer to the antenna trace on the top layer of the TPU. However, there is a challenge to solve to have proper feeding for the antenna. The SMA connectors that were available either they are PCB or SMD connectors, as shown in Figure 18 (a,b), respectively.

(a) (b)

Figure 18. Different types of SMA connectors.

PCB connector has four legs as shown in Figure 18 (a), it has a major disadvantage which is the reliability and the mechanical stability of the feeding of the antenna, the reason for that is the nature of the TPU which is used as a substrate since it is very flexible and stretchable. Therefore, it is very hard to ensure a very stable feeding if the PCB connector shown earlier is utilized. Hence, the original shape of the PCB SMA connector cannot be used as-is. The other option is SMD connectors, from the point of mechanical stability of the feed and the reliability, then it is a good option. However, the main problem with this type of SMA connector is that its ground plane is taking a circular shape as shown in Figure 19 (a), that means that when the SMA is installed properly on the TPU bottom layer, half of the ground plane of the SMA will be directly connected to the ground plane of the TPU itself. However, the other half of the SMA will create an extended ground plane beneath the antenna itself, as shown in Figure 20 (c) if it is considered that the visible material represents the bottom view of the SMA connector, then, it is clear that the size of that extended ground is almost half of the antenna size, which can effectively affect the antenna performance. Hence, the solution presented in this thesis, is that I cut the front legs of the SMA connector as shown in Figure 19 (b), where the back legs, will be connected and glued to the ground plane of the TPU as shown in Figure 20 (a) while filling the gap between the SMA and the antenna with a stripboard as shown in Figure 20 (b) and (c). this solution was giving very good reliability in terms of its mechanical stability and support both for making the TPU a bit more fixed at the feeding point, as well as giving the SMA connector a rigid connection point. Finally, I glued the supporting material with a supportive adhesive Loctite 3525 [42] that gives extra stability to the glued components so that it can stand more stretching force without being disconnected. The back legs of the SMA connector are then glued with conductive adhesive Eccobond 56C [43] as well as supportive glue Loctite 3525. Loctite 3525 supporting adhesive is also used on the top layer to keep the SMA feeding tip always connected to the antenna trace. Now the antenna is ready for measurements. It is also worth mentioning that 50Ω SMA feeding is used in order to overcome impedance mismatch problems that will be even more complex to overcome under stretching effect.

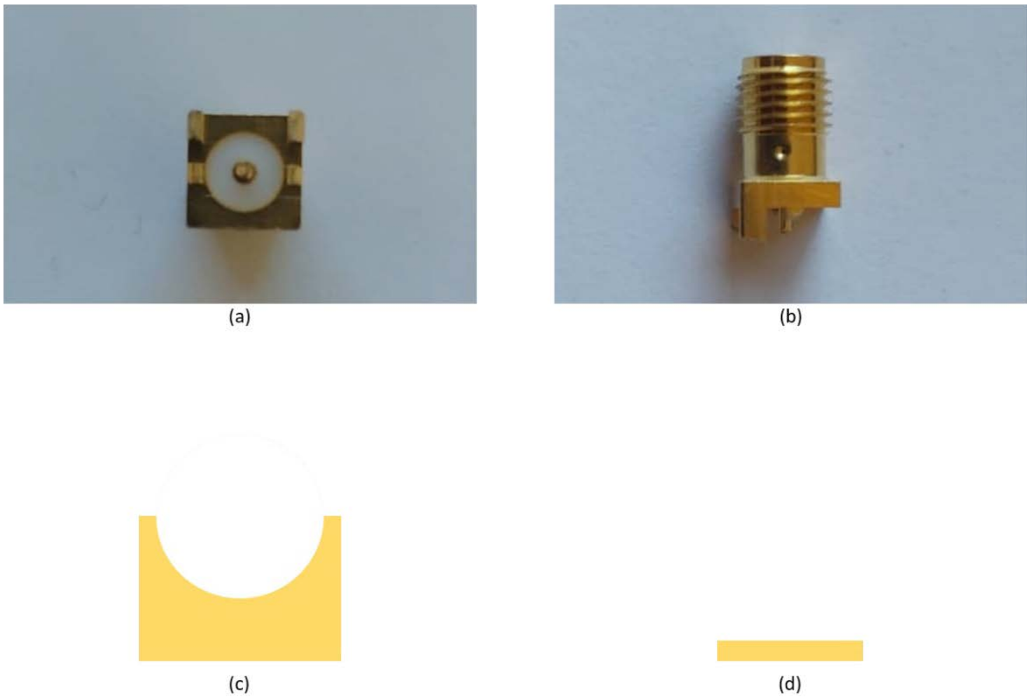


Figure 19. SMA connector used to feed the meandered monopole antenna, a) view from the bottom, b) side view, c) support material plan view, d) support material side view.

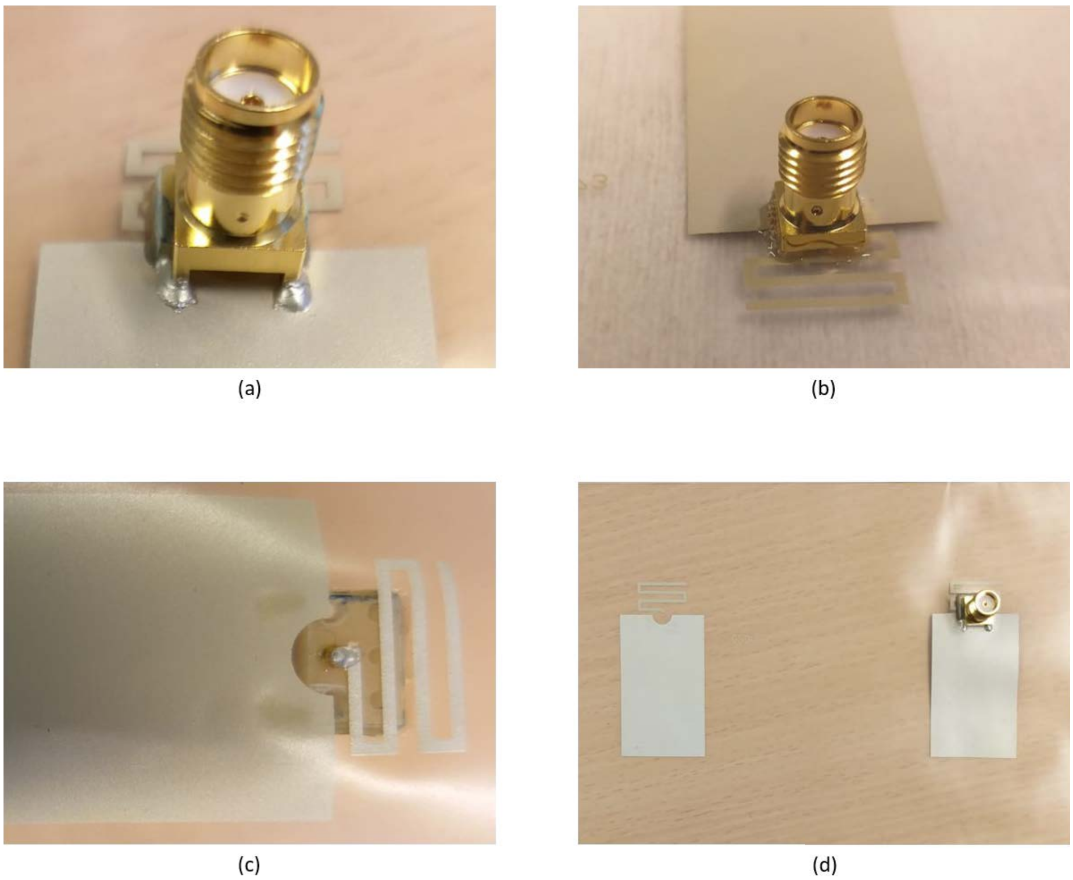


Figure 20. Assembled meandered monopole antenna with SMA connector.

4 SIMULATION AND MEASUREMENT RESULTS

In this chapter, I will list all simulation and measurement results for dipole and meandered monopole antenna. HFSS was used for all simulations listed in this chapter. In addition, I have designed and simulated patch antenna including the stretching effect on the antenna radiation behavior, however, I will not be listing any of its simulation results because the performance obtained was extremely poor compared to the other antenna, it couldn't even be considered as an antenna but rather a poor radiator. The reason for that is the TPU thickness; in this thesis, the TPU thickness of 100 to 150µm is used, which is extremely thin for a patch antenna to operate normally. For that reason, the patch antenna will not be reported as part of this thesis.

4.1 Dipole antenna simulation results

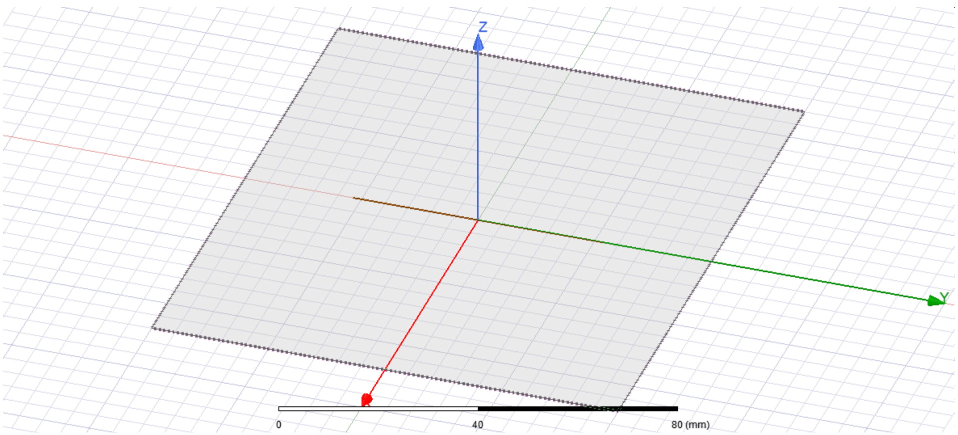


Figure 21. The design of the simulated dipole antenna.

In this section, I will list the simulation results of the dipole antenna shown in Figure 21, where the dipole is along the y-axis. For the dipole antenna, two different antennas were simulated, which corresponds to two different substrates which are, TPU_U073, TPU_U9122. For each substrate, three simulation setups were conducted, which corresponds to different stretching models which are, no stretching, stretching over the length of the dipole, stretching over the width of the dipole.

Table 5. Common dipole design parameters

Parameter Name	**Value**
Substrate length	120 mm
Substrate width	100 mm
Dipole width	0.3 mm
Dipole's feeding point gap	0.2 mm

Table 6. Variant design parameters

Parameter Name	**TPU_U073**	**TPU_ID9211**
Quarter wavelength	26.6 mm	26.1 mm
Substrate thickness	100 µm	150 µm

4.1.1 Stretching over length

Since the dipole antenna's resonance frequency is based on the length of the dipole itself, hence stretching over the length of the dipole antenna heavily affects the resonance frequency and reduce it to lower frequencies, because the resonance frequency is inversely proportional to the length of the dipole. Stretching means a positive increase in a dimension's value, which means that the length is going to always increase. Hence, the resonance frequency decreases, and impedance mismatch increases at the original frequency. Depending on the original bandwidth of the antenna and the stretching percentage, the antenna might still radiate at the original frequency based on the amount of stretching imposed and based on the effect of the stretching on the antenna bandwidth. However, even if the dipole antenna still radiates after being stretched, more impedance mismatch occurs, and as a result, the antenna is less efficient.

Figure 22 and Figure 23 shows the S11 of the dipole antenna for both substrates TPU_U073 and TPU_ID9122, respectively. Each of the figures has six different curves where each of the curves corresponds to a different stretching percentage, starting at relaxed no stretching up to 50% strain over the length of the dipole. The resonance frequency for 0% corresponds to S11 of around -27 dB for the TPU_U073 as well as the TPU_ID9122. The more the stretching is, the more the mismatch occurs at the nominal frequency, this can be seen from the Z11 of both substrates for different stretching percentages, as shown in Figure 24 and Figure 25 for TPU_U073 and TPU_ID9122 respectively. In addition, I have included the simulation results for the VSWR to view the effect of the impedance mismatch, as shown in Figure 26 and Figure 27 for TPU_U073 and TPU_9122, respectively. The figures also show that at different stretching percentages, the antenna is resonating at different lower frequencies compared to the nominal frequency. For instance, In Figure 22, at 10 percent stretching, the antenna is resonating at 2.23 GHz with S11 around -25 dB, Figure 24 shows very good impedance matching at 2.226 GHz for 10% stretching. The same behavior is seen when the antenna is utilizing TPU_ID9122 as a substrate. This behavior will be useful where a stretchable dipole is utilized as a tunable antenna.

According to the simulations which we have performed, at 10% stretching over the length of the dipole, the dipole is no longer radiating at the original resonance frequency when it is not stretched. However, we have experimented with up to 50% stretching in order to show the consistency of the stretching behavior and to compare it with the effect of stretching over the width of the antenna.

Stretching the Dipole antenna over its length from 0% up to 50% shows consistent behavior regardless of the TPU substrate. The resonance frequency of the dipole antenna is very sensitive to the stretching over its length. To summarize, I will list the effect of stretching on the dipole antenna when stretched over its length on the following parameters:

- Effect on resonance frequency: stretching over the length of the dipole or the monopole antenna is inversely proportional to the resonance frequency, if the dipole length increases due to stretching, expect the resonance frequency to be reduced backward.
- Effect on bandwidth: simulation results did not show that stretching over length affects the bandwidth of the dipole antenna.
- Effect on efficiency: as the antenna is stretched over its length, the efficiency decreases because the impedance mismatch increases, and more losses occur.

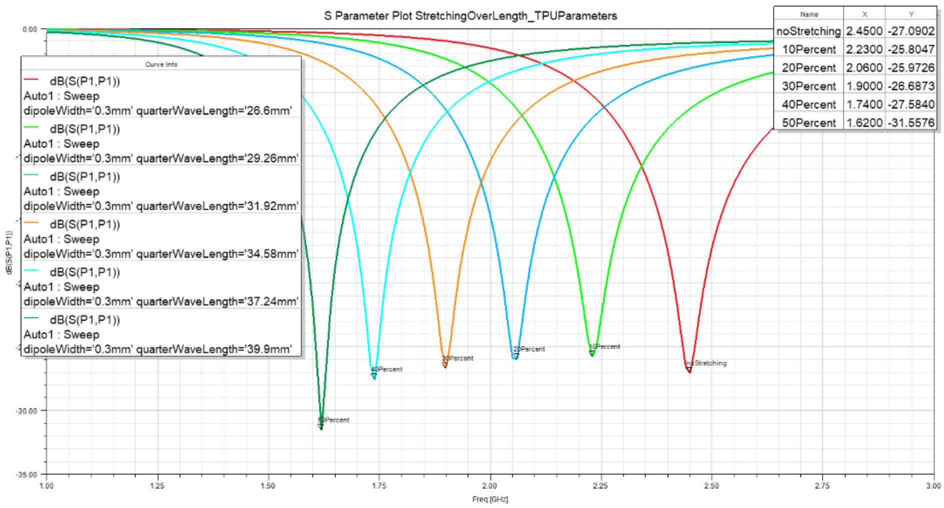


Figure 22. Dipole antenna on TPU_U073: S11 parameters, when stretched over its length.

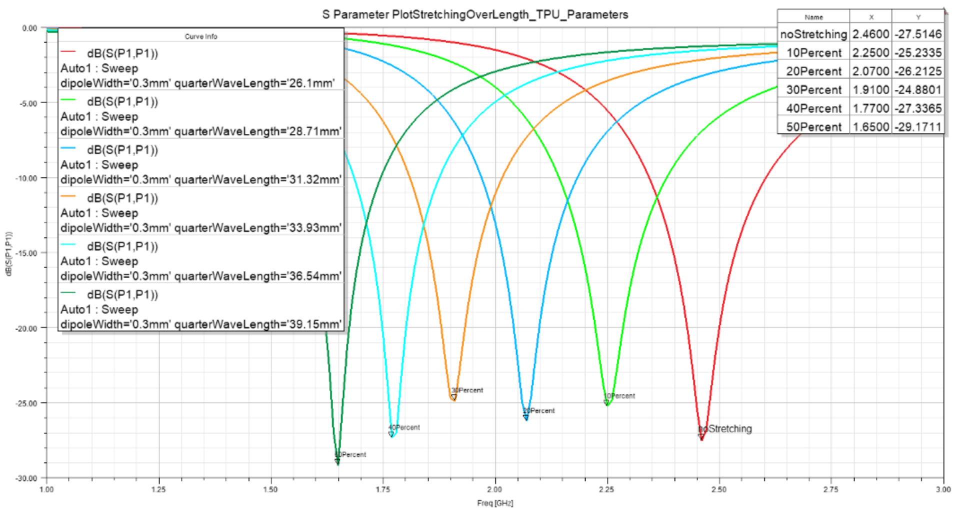


Figure 23. Dipole antenna on TPU_ID9122: S11 parameters, when stretched over its length.

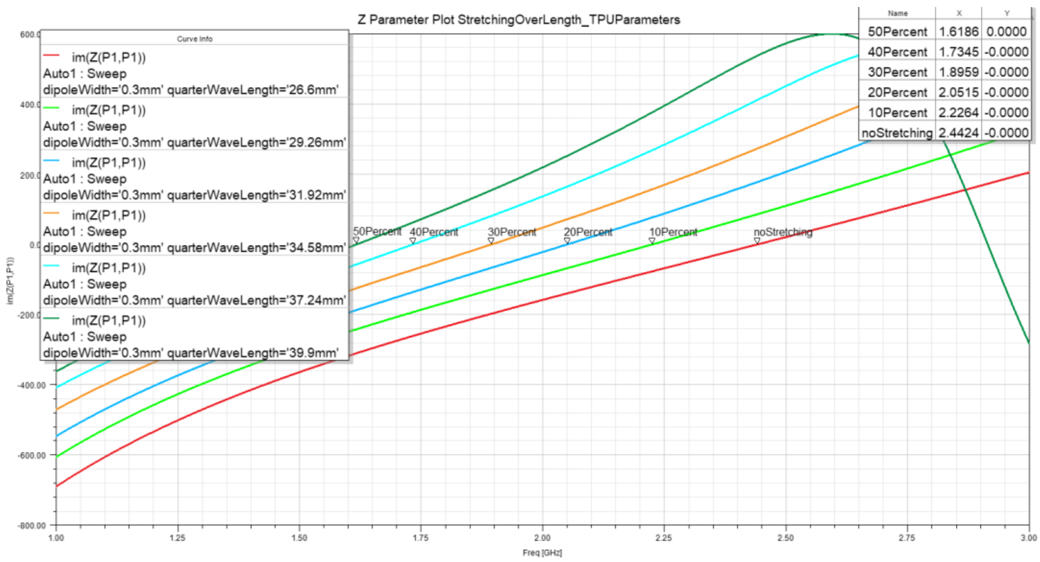


Figure 24. Dipole antenna on TPU U073: Imaginary part of Z11 parameters, when stretched over its length.

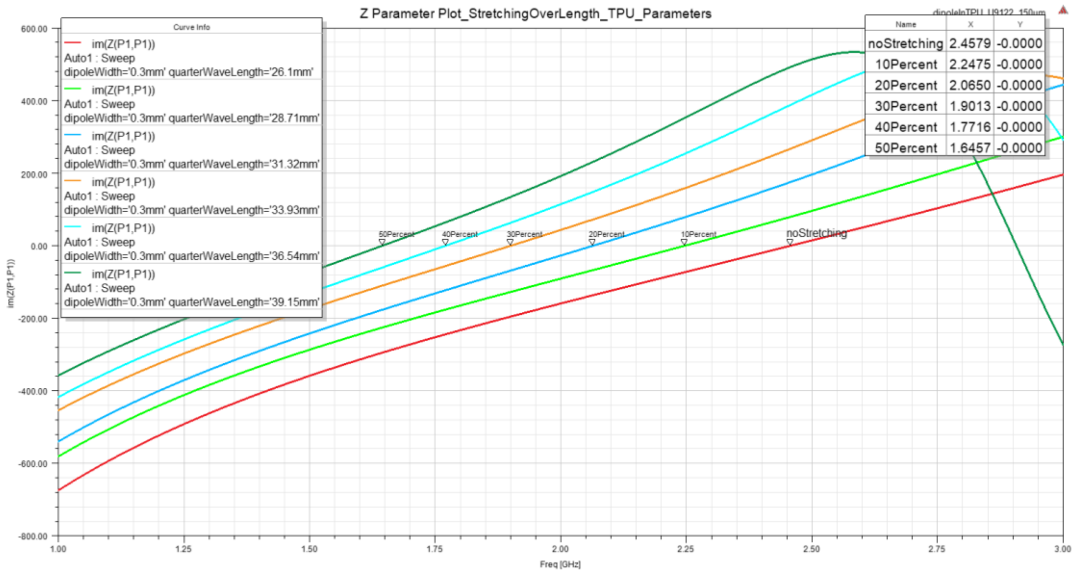


Figure 25. Dipole antenna on TPU ID9122: Imaginary part of Z11 parameters, when stretched over its length.

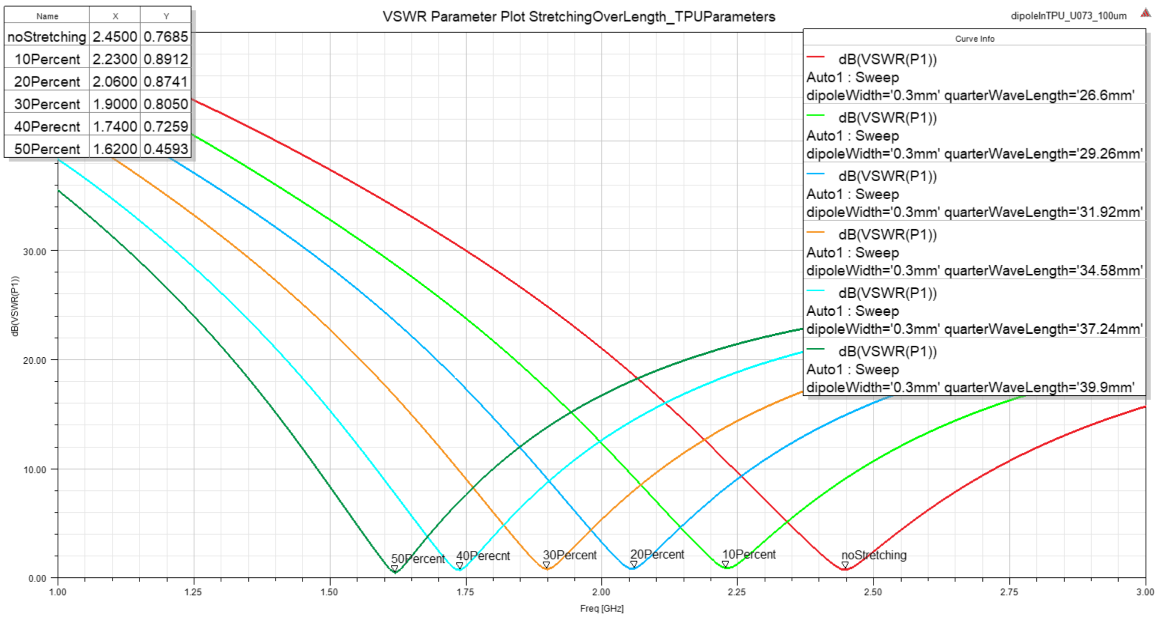


Figure 26. Dipole antenna on TPU U073: VSWR, when stretched over its length.

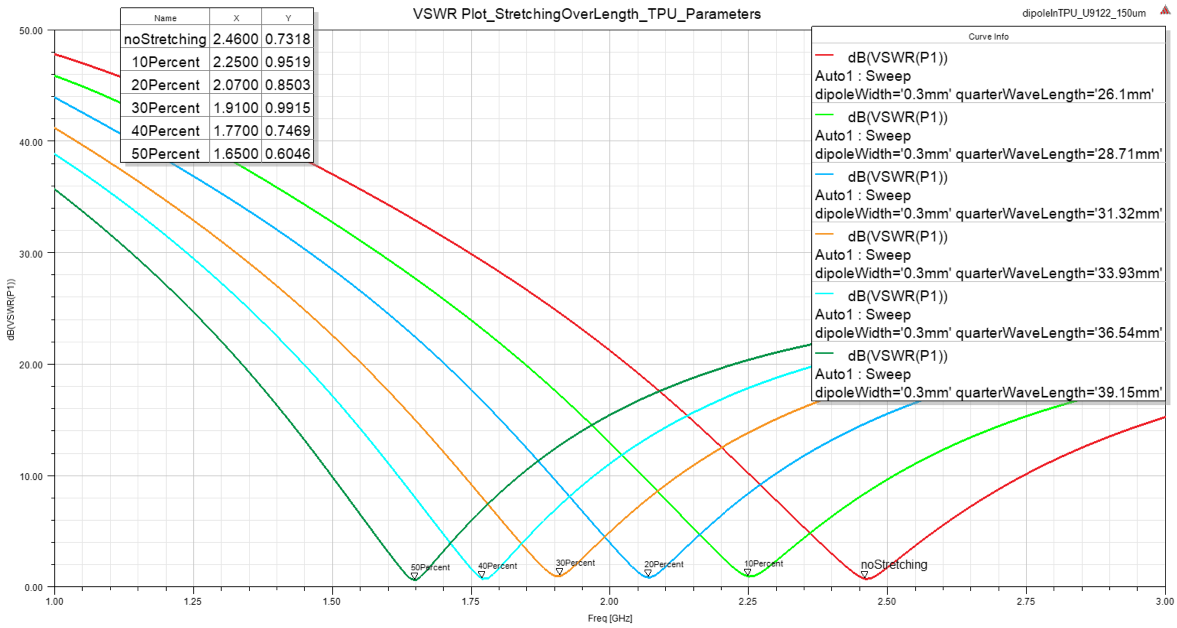


Figure 27. Dipole antenna on TPU ID9122: VSWR, when stretched over its length.

4.1.2 Stretching over width

The nature of the dipole or monopole antenna makes its radiation properties very sensitive to the stretching performed over the length of the dipole or monopole. However, dipole or monopole antennas are not very sensitive to stretching effects that occur over its width. In this thesis, we conducted some simulations where we stretched the dipole over its width from 0.3mm up to 1mm. Figure 28 and Figure 29 shows the S11 for the dipole antenna when stretched over its width for both substrates TPU_U073 and TPU_ID9122, respectively. For instance, in Figure 28 the S11 is equal to -27 dB when the antenna is not stretching resonating at 2.45 GHz, as the antenna is stretched over its width up to 1 mm which corresponds to 330% of its original width we can observe a small change of the resonance frequency where it moves to 2.49 with S11 of -27.7. In addition, the antenna shows very stable impedance matching, this can be seen from the VSWR shown in Figure 30, and Figure 31 for TPU_U073 and TPU_ID9122 respectively, where the impedance of the unstretched dipole is almost equal to 0.76 while it is around 0.71 when the antenna is stretched over its width from 0.3 mm to 1 mm. Hence, the radiation properties are almost the same, no matter how much stretching was imposed. Also, the dipole shows consistent behavior regardless of what TPU is used. The fact that dipole or monopole antennas are not very sensitive to stretching over its width will give very useful features that will be utilized later and mentioned in the guidelines for antenna selection, design, and placement for non-antenna specialists in the next chapter.

To summarize, I will list the effect of stretching on the dipole antenna when stretched over its width on the following parameters

- Effect on resonance frequency**:** stretching over the width of dipole or monopole antenna has very little effect on the antenna resonance frequency.
- Effect on bandwidth**:** simulation results did not show that stretching over width heavily affects the bandwidth, however from antenna theory, we know that width has an effect on the antenna bandwidth, the wider the width of a monopole or dipole, the wider the bandwidth is.
- Effect on efficiency**:** according to our simulations, as the antenna is stretched over its width, its radiation properties were almost the same, including the impedance. Hence, the

losses due to the mismatch are minimal, which means the stretchability over the width of a dipole or monopole antenna has little effect on the antenna efficiency.

Table 7. Effect of stretching the dipole antenna over its length and width on resonance frequency, bandwidth, and efficiency

Parameter	**Stretching over length**	**Stretching over width**
Resonance Frequency	Decrease	Almost constant
Bandwidth	Almost not affected but will decrease in reality	Almost not affected, but will increase in reality
Efficiency	Decrease	Almost the same

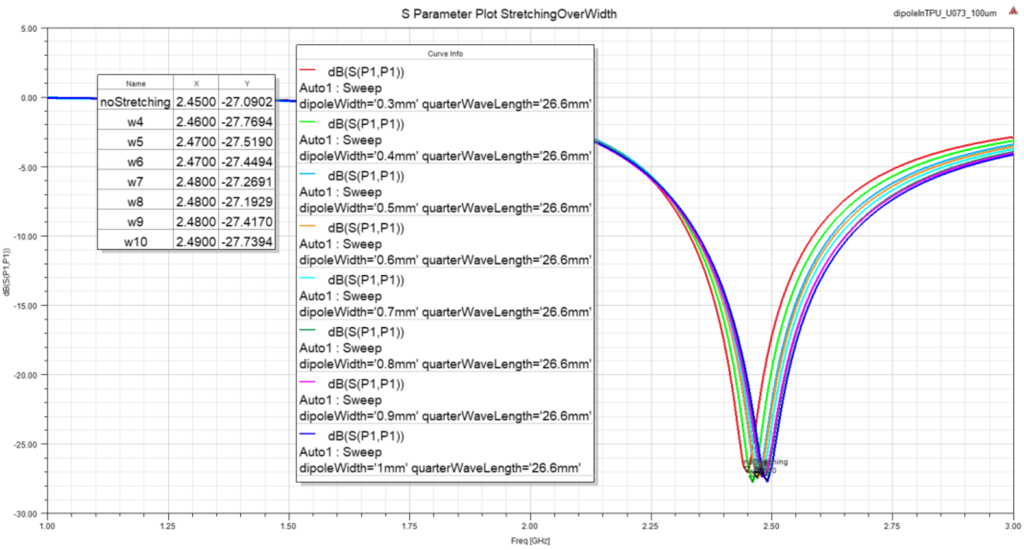


Figure 28. Dipole antenna on TPU U073: S11 parameter, when stretched over its width.

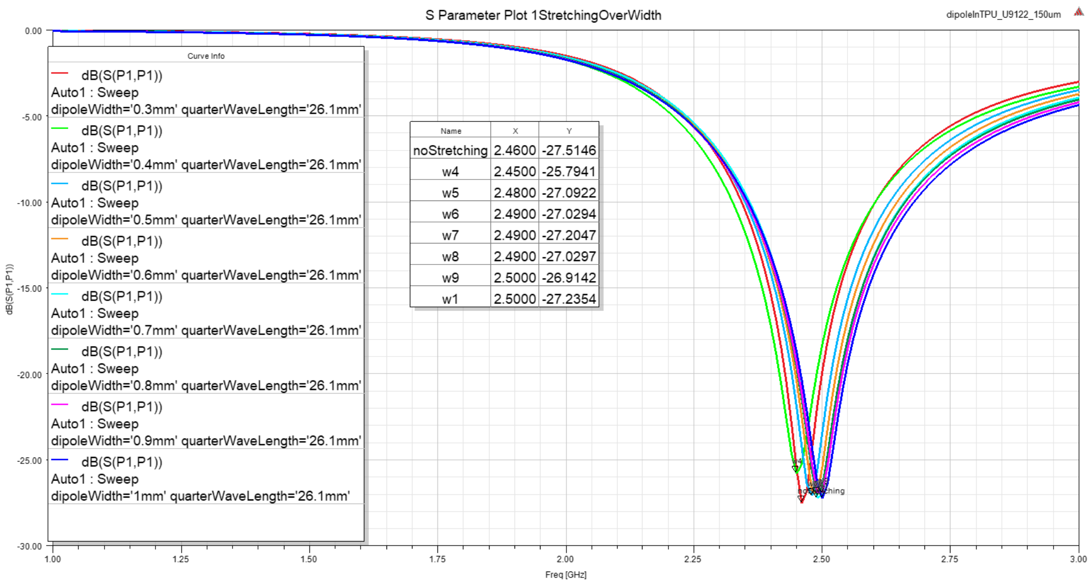


Figure 29. Dipole antenna on TPU ID9122: S11 parameter, when stretched over its width.

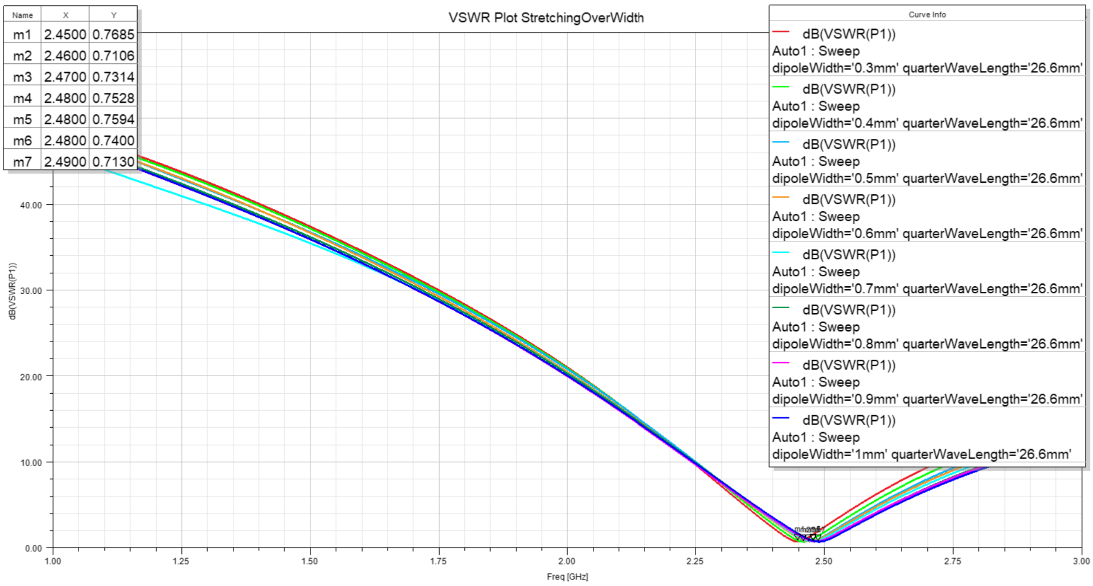


Figure 30. Dipole antenna on TPU U073: VSWR, when stretched over its width.

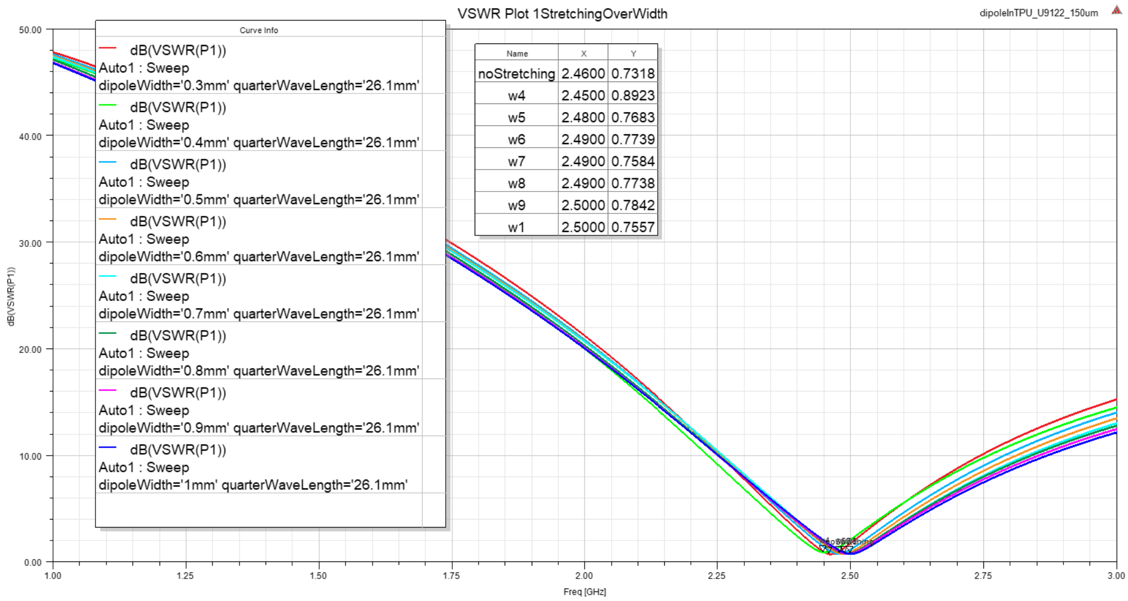


Figure 31. Dipole antenna on TPU ID9122: VSWR, when stretched over its width.

4.2 Meandered planar monopole antenna simulation results

In this section, I will list the simulation results of the meandered monopole antenna shown in Figure 32, further analysis and insights will be discussed in the next chapter.

For the meandered monopole antenna, two different antennas were simulated, which corresponds to two different substrates which are, TPU_U073, TPU_ID9122. For each substrate, two simulation setups were conducted, which corresponds to different stretching models that are stretching over the x-axis, stretching over the y-axis.

For each substrate, different Antenna Dimensions are used in order to have the resonance frequency as close as possible to the 2.45 GHz, but, it is not necessarily resonating at 2.45 GHz since the main goal of this study is to see the effect of stretching on the antenna regardless of the exact resonance frequency. Table 4 shows the dimensions for the meandered monopole antenna for each substrate.

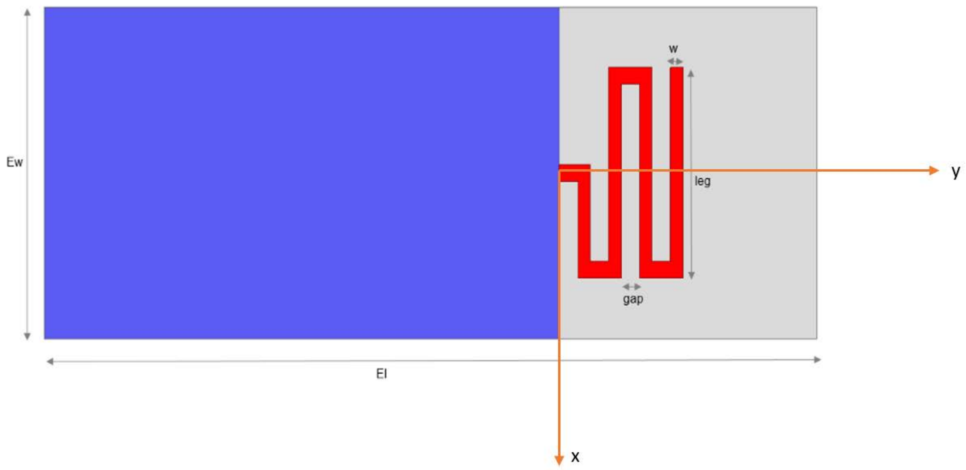


Figure 32. Meandered monopole antenna.

4.2.1 Stretching over x-axis

In this section, simulation results for the meandered monopole antenna are presented when the antenna is stretched over the x-axis as shown in Figure 32. Figure 33 and Figure 34 show S11 for the meandered monopole antenna for both substrates TPU_U073 and TPU_ID9211, respectively. The antenna is simulated at different stretching percentages that are 0%, 5%, 10%, and 20%. For each stretching percentage, the resonance frequency is pulled backward, and this is consistent with the radiation principle of the monopole antenna, the performance of the antennas on both TPUs are almost the same. It is also clear that the more stretching is imposed on the antenna, the worse the matching becomes at the new resonance frequency as well as the original resonance frequency before stretching, Unlike the dipole antenna results that were presented in the previous section. This can be clear when checking Z11 in Figure 35 and Figure 36 for TPU_U073 and TPU_ID9122, respectively. In addition to Z11, VSWR can also show the effect of the impedance mismatch for different stretching percentages, as shown in Figure 37 and Figure 38 for TPU_U073 and TPU_ID9122, respectively.

In Figure 33, the resonance frequency was pulled back from 2.45 GHz when TPU_U073 is stretched to 2.38 GHz at 5% stretching, while the S11 magnitude is dropped from -33.18dB at zero stretching percentage to -27.57dB at 5% stretching percentage. Figure 33 also shows consistent behavior for the degradation of S11 when the TPU is stretched from 0% to 5% and from 5% to 10% it is noticed that the behavior is consistent, that is around to 0.7 GHz shift in the resonance frequency backward and around 5dB drop in the S11 magnitude. Figure 34 shows the same simulation behavior that Figure 33 presents but for TPU_ID9211. The behavior is almost the same, except it is observed that S11 shows slightly better values.

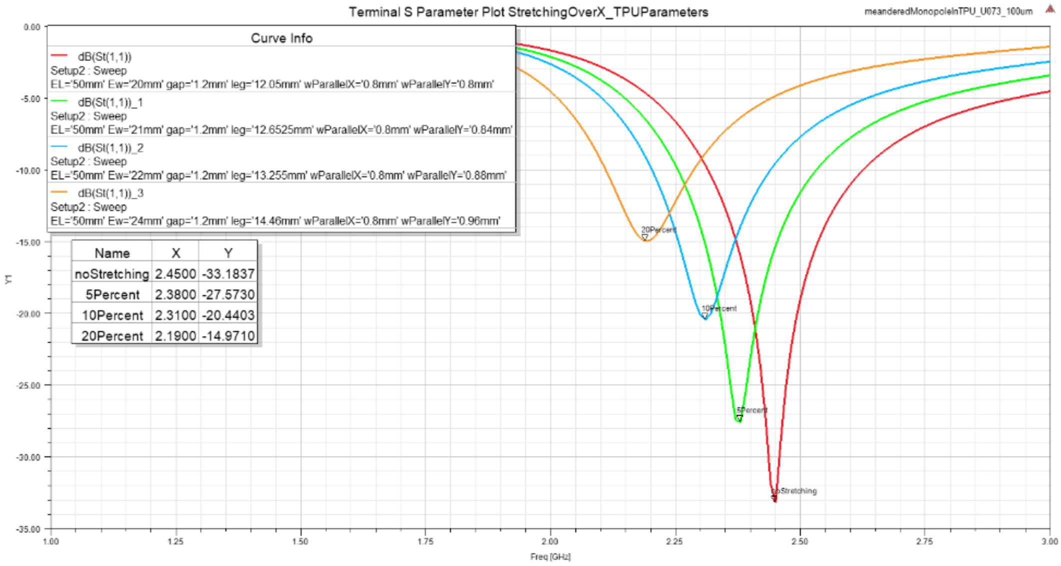


Figure 33. S11 of Meandered monopole antenna on TPU_U073, stretched over the x-axis

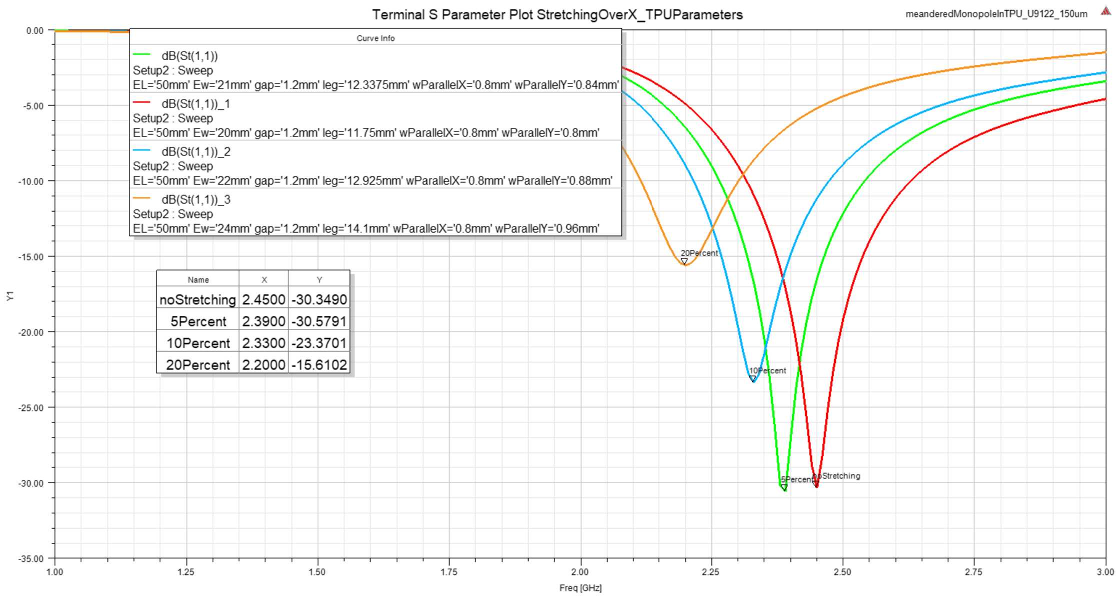


Figure 34. S11 of Meandered monopole antenna on TPU_ID9211, stretched over the x-axis

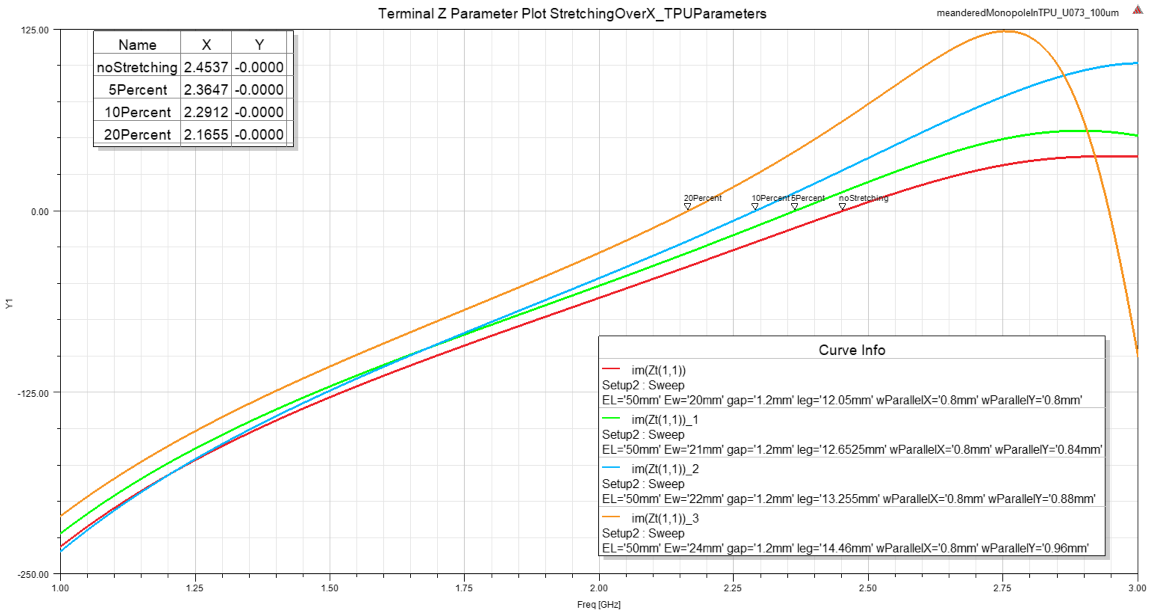


Figure 35. The imaginary part of Z11 of meandered monopole antenna on TPU U073 stretched over the x-axis.

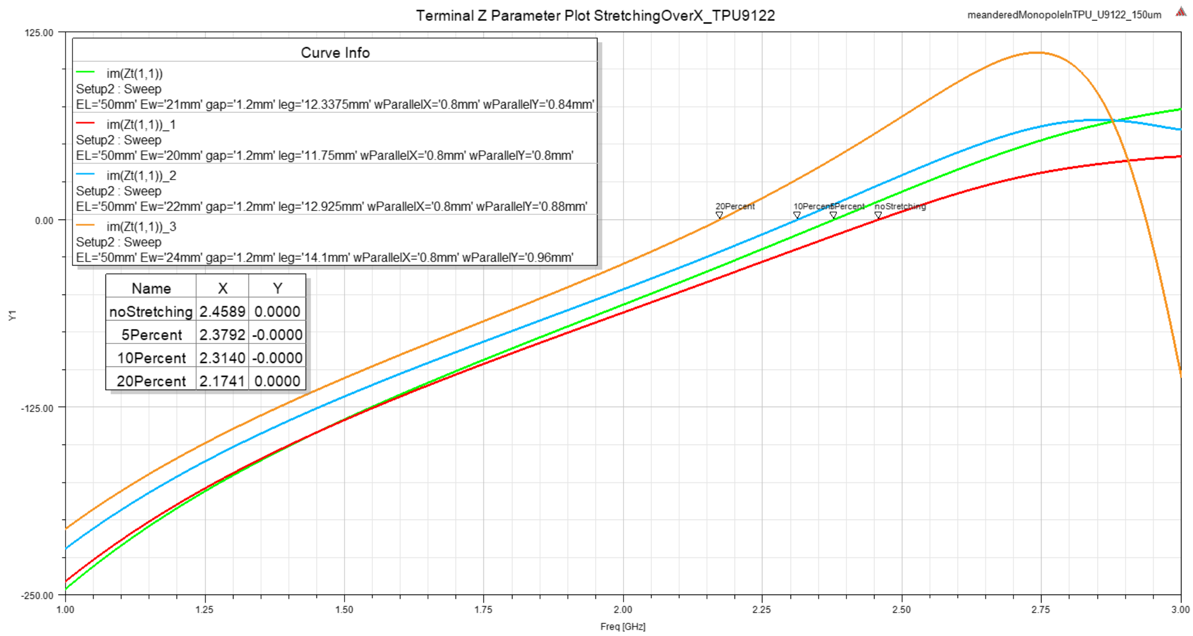


Figure 36. The imaginary part of Z11 of meandered monopole antenna on TPU_ID9211 stretched over the x-axis.

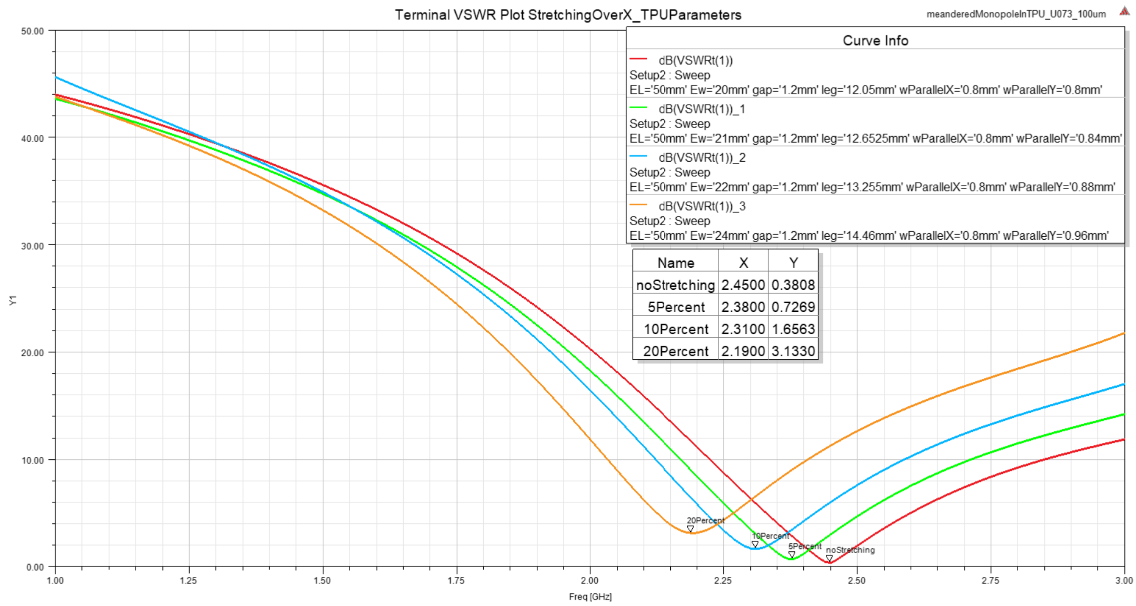


Figure 37. VSWR of meandered monopole antenna on TPU_U073 stretched over the x-axis.

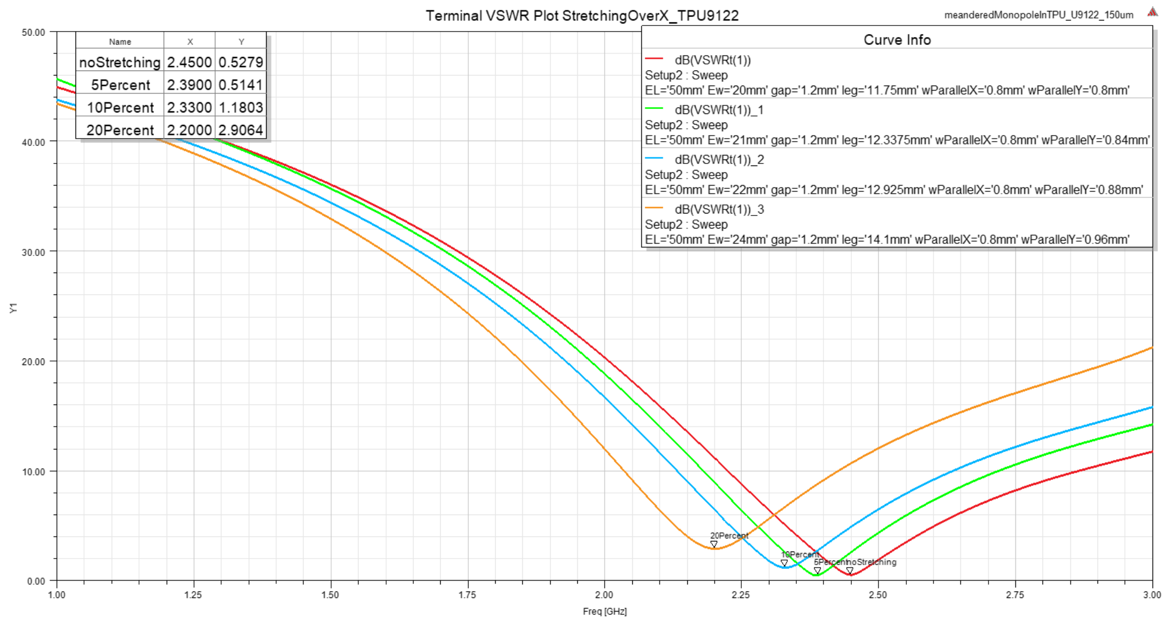


Figure 38. VSWR of meandered monopole antenna on TPU_ID9122 stretched over the x-axis.

4.2.2 Stretching over y-axis

In this section, simulation results for the meandered monopole antenna are presented when the antenna is stretched over the y-axis, as shown in Figure 32. Figure 39 and Figure 40 show S11 for the meandered monopole antenna for both substrates TPU_U073 and TPU_ID9211. The antenna is stretched at different stretching percentages 0%, 5%, 10% and 20%. For each stretching percentage, the resonance frequency is pulled backward, and this is consistent with the radiation principle of the monopole antenna. The performance of both TPUs is almost the same. It is also clear that the more stretching is imposed on the antenna, the worse the matching becomes at the new resonance frequency as well as the original resonance frequency before stretching. This can be clear when checking Z11 in Figure 41, Figure 42 for TPU_U073 and TPU_ID9122, respectively. In addition to Z11, VSWR can also show the effect of the impedance mismatch for different stretching percentages, as shown in Figure 43 and Figure 44 for TPU_U073 and TPU_ID9122, respectively.

Based on the previous simulation results of the monopole antenna, the monopole antenna shows an interesting property for stretchable applications, which is that the antenna shows symmetric response to stretching over its x-axis or y-axis.

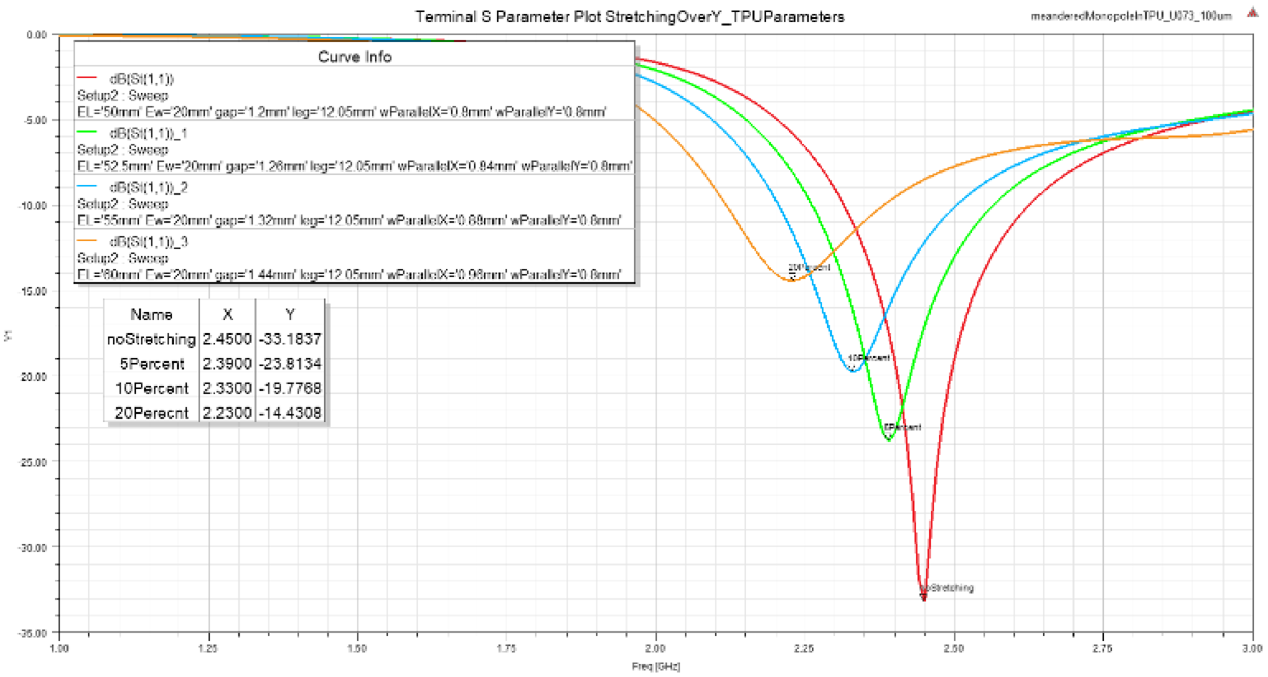


Figure 39. S11 of meandered monopole antenna on TPU_U073 stretched over the y-axis.

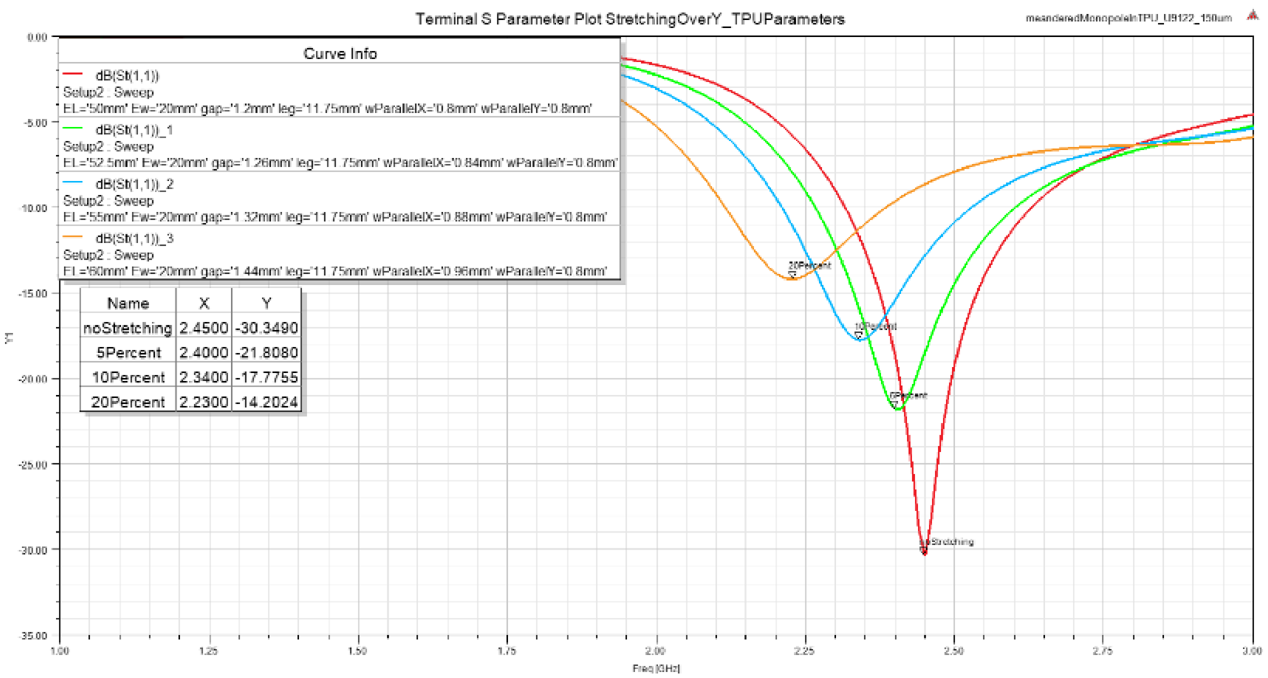


Figure 40. S11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis.

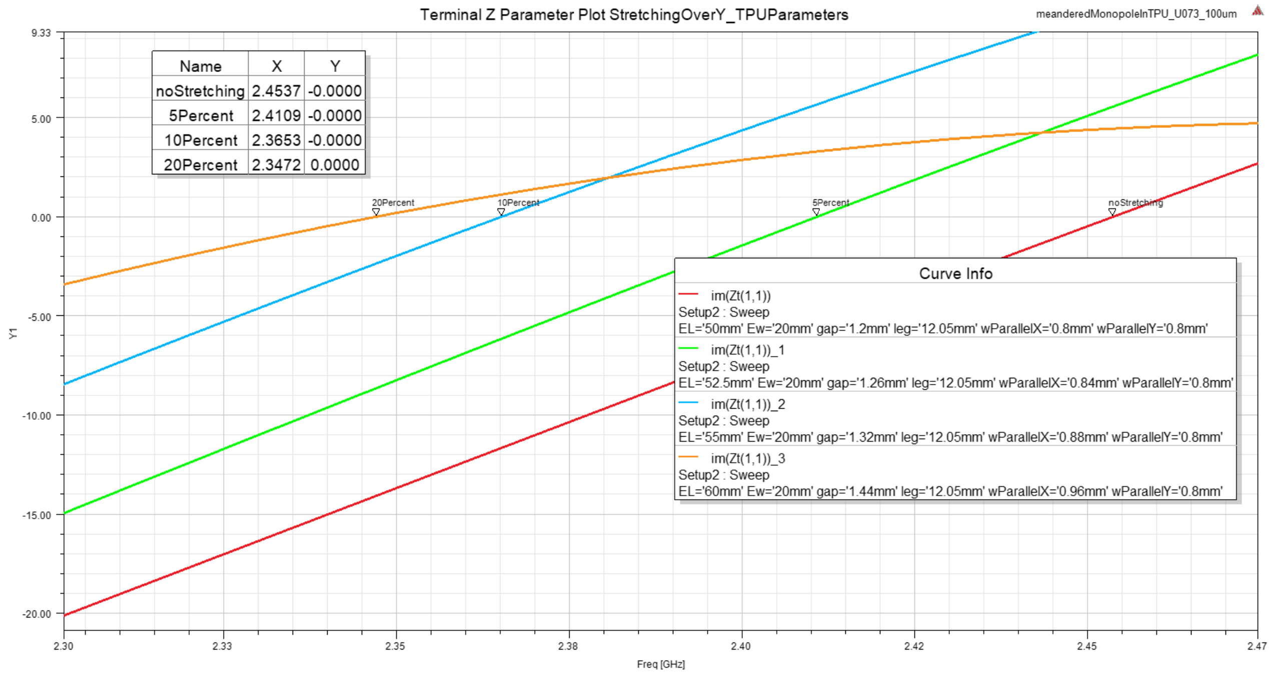


Figure 41. The imaginary part of Z11 of meandered monopole antenna on TPU_U073 stretched over the y-axis.

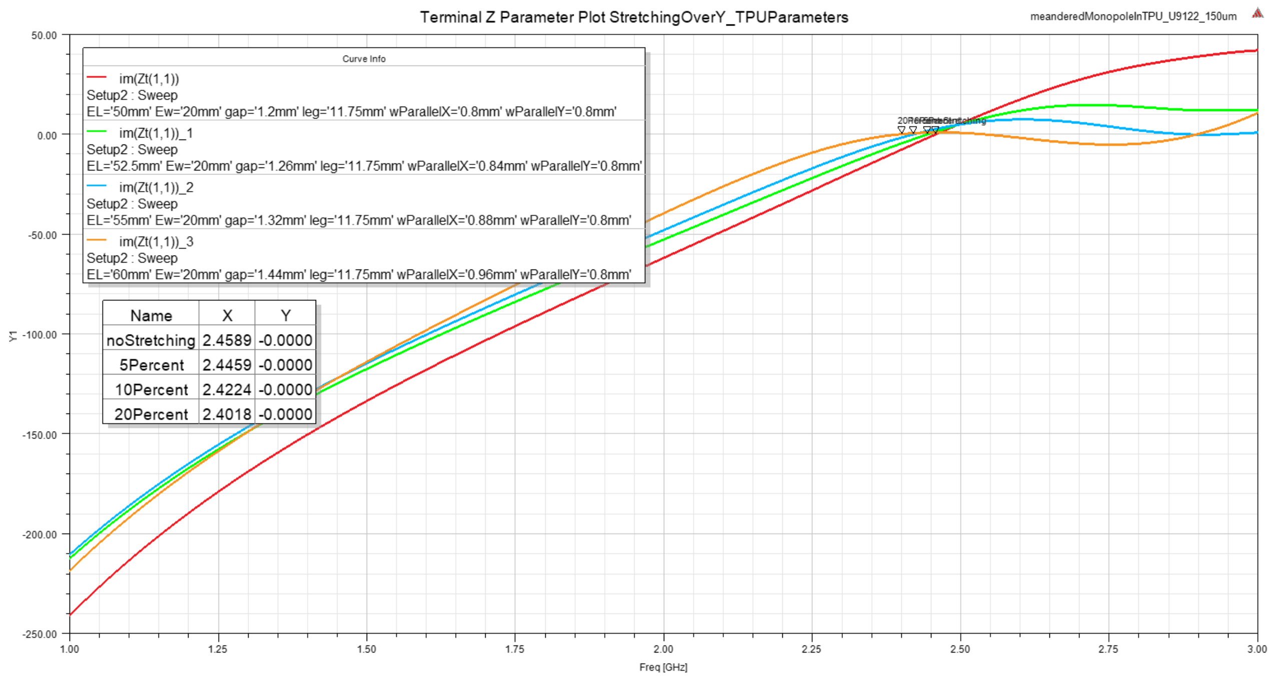


Figure 42. The imaginary part of Z11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis.

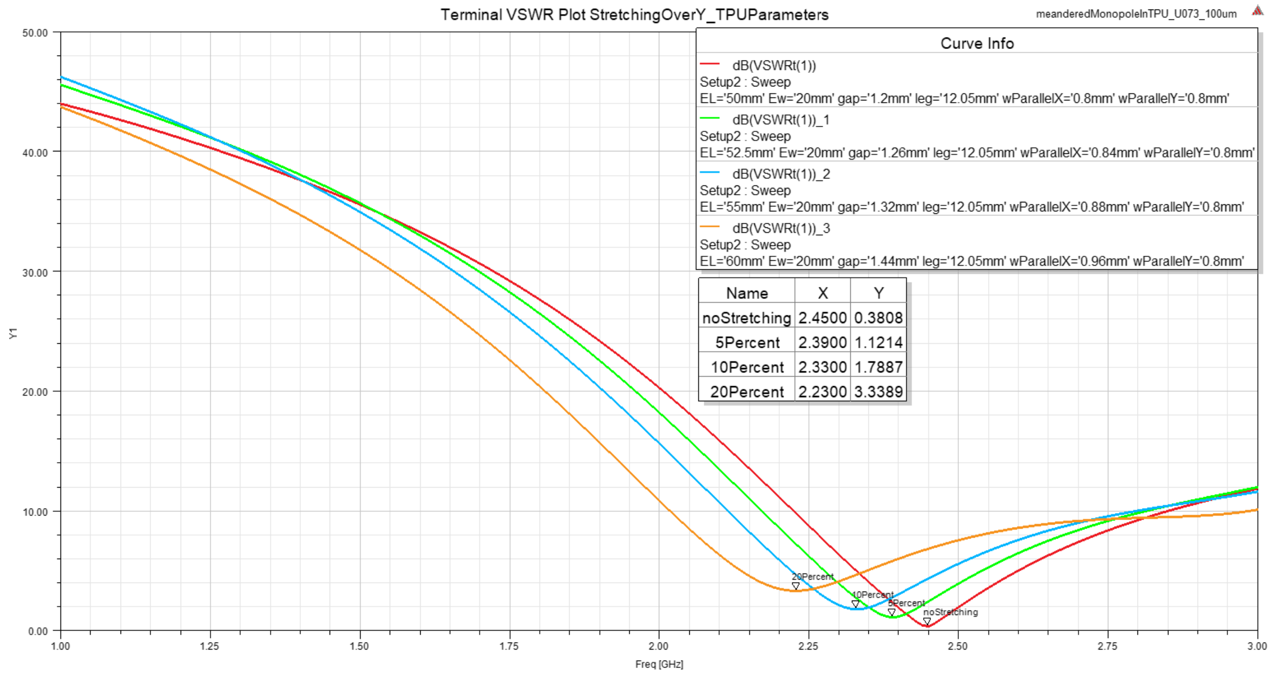


Figure 43. VSWR of meandered monopole antenna on TPU_U073 stretched over the y-axis.

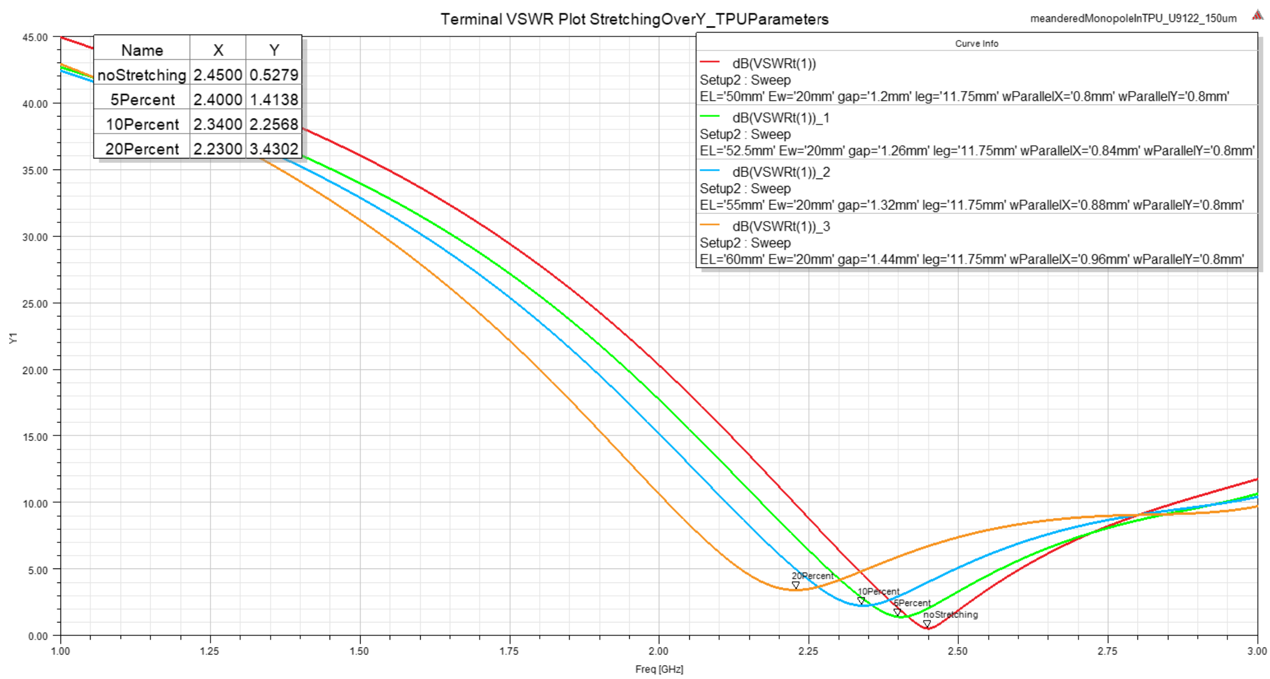


Figure 44. VSWR of meandered monopole antenna on TPU_ID9122 stretched over the y-axis.

4.3 Meandered monopole antenna measurement results

In this section, I will discuss the measurement setup, as well as the results for the meandered monopole antenna. It was very challenging to get the antenna tested due to the lack of measurement tools and the complexity of the experiment itself due to the flexible and stretchable nature of the substrate. The main challenge was to find a way where I can stretch the TPU to a certain percentage, fix the antenna in that position, and then do the measurements, while not affecting the antenna performance. This was not the end of the challenges which I had to face. One more challenge was to do all these measurements with a VNA that does not have a USB port to save our measurement results. A senior RF specialist at VTT Oulu, Antti H. Tanskanen, was able to extract the measurement results using a floppy disk. Eventually, with the help of Arttu Korhonen who is a research scientist at VTT Oulu, I was able to prepare testing tools that are utilized to test the stretchability of TPUs in general, I used a stretching machine Mark-10 ESM303 shown in Figure 45 and Figure 46, it has two clips that can hold the TPU from both sides top and bottom, then these clips hold tight the antenna in between. Then using a program which is built using LabVIEW (Laboratory Virtual Instrument Engineering Workbench) and programmed by Arttu Korhonen, where I can send stretching order to the machine and repeat the same experiment for multiple times, this was extremely useful setup that made the measurement process less challenging. The measurement results of the meandered monopole antenna have shown very interesting results, which makes the meandered monopole antenna a very good choice for many stretchable applications.

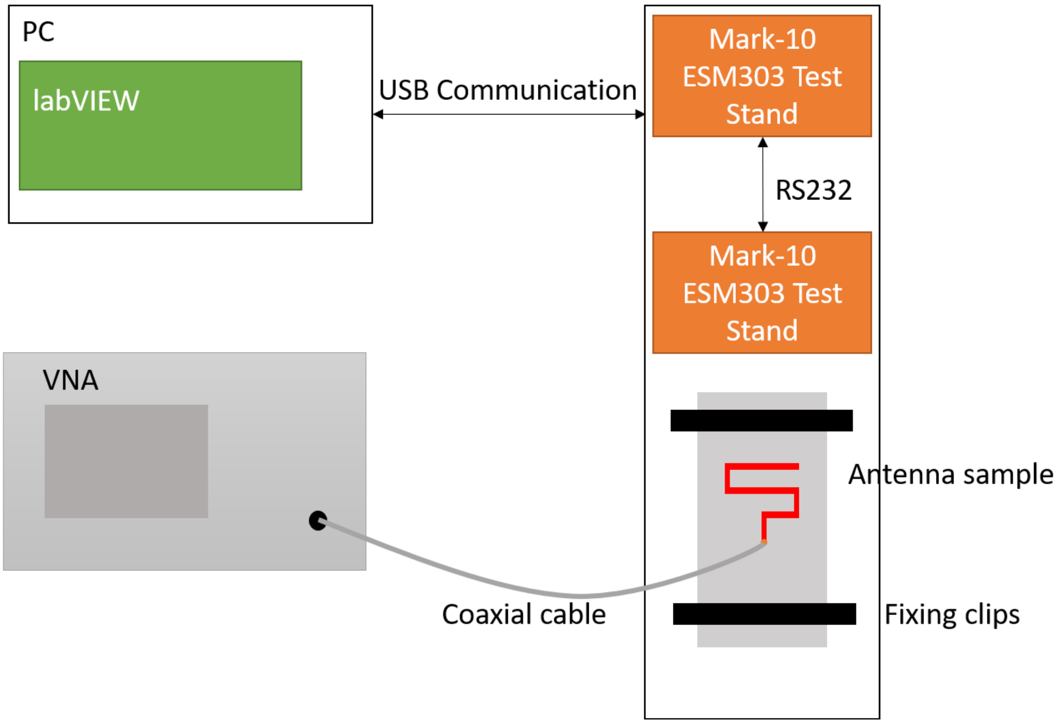


Figure 45. Test setup block diagram.

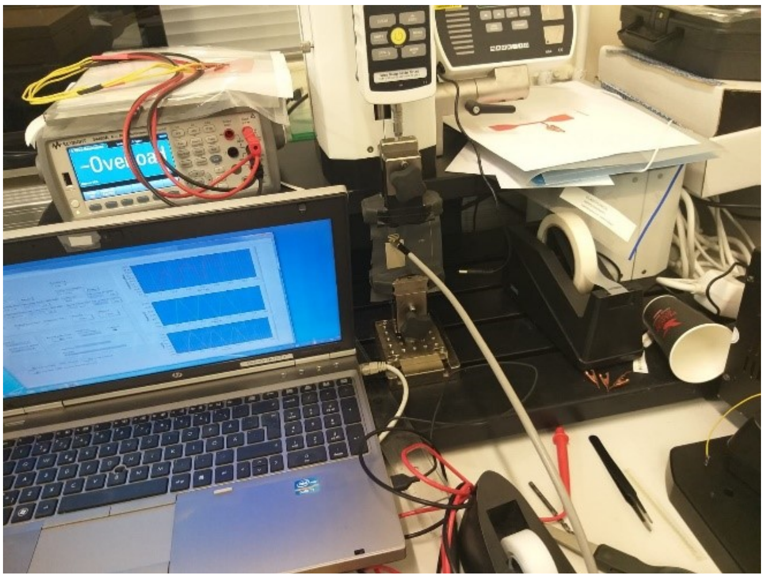


Figure 46. Measurement setup.

4.3.1 Stretching over x-axis

I have performed the measurements on the meandered monopole antenna when it is stretched on both directions x-axis and y-axis. In this section, I will present and quickly discuss the measurement results when the antenna is stretched over the x-axis. Table 8 shows a summary of the measurements obtained when stretching the meandered monopole antenna over the x-axis.

In this experiment, I measured multiple antennas with different inks and TPUs, however, only TPU_U073 is reported, however, to show the effect of different TPUs, TPU_ID9211 is reported in the measurements done over the y-axis in the following section. The measurement shows no difference in performance for different antennas that are utilizing different inks, hence I reported only single ink measurements, which is CI-1036. I have to mention again that obtaining these results was very challenging due to the complex measurement setup, which was unstable by nature, however, I repeated the experiment as many times as possible so that I can see some stabilization in the antenna performance. The results obtained by the measurements are relatively acceptable compared to the simulation results.

Table 8. Summary of measurement results for meandered monopole antenna stretched over the x-axis

Figure	**TPU substrate**	**Stretching Percentage**	**Frequencies**	**S11**
Figure 47	U073	5%	2.45 GHz	-8.7 dB
			2.27 GHz	-10.8 dB
Figure 48	U073	10%	2.45 GHz	-10.60 dB
			2.27 GHz	-13 dB
Figure 49	U073	20%	2.45 GHz	-8.17 dB
			2.15 GHz	-13 dB

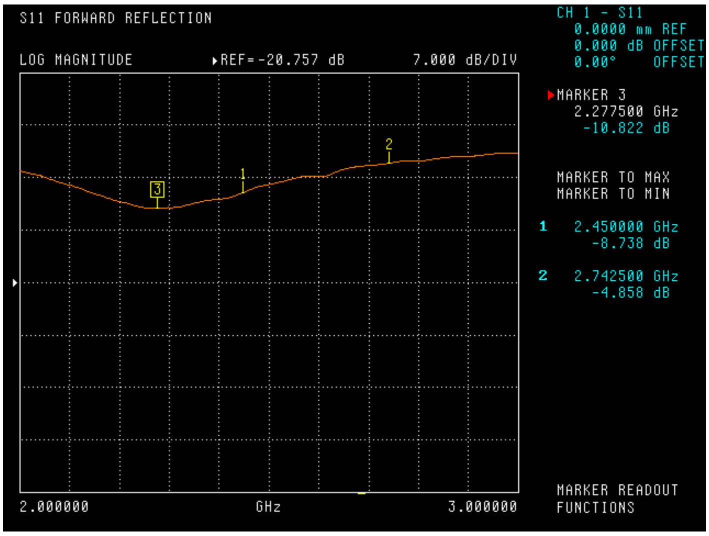


Figure 47. S11 of meandered monopole antenna on TPU_U073, stretched over the x-axis, with Ink CI-1036, while stretched for 5% of its original length.

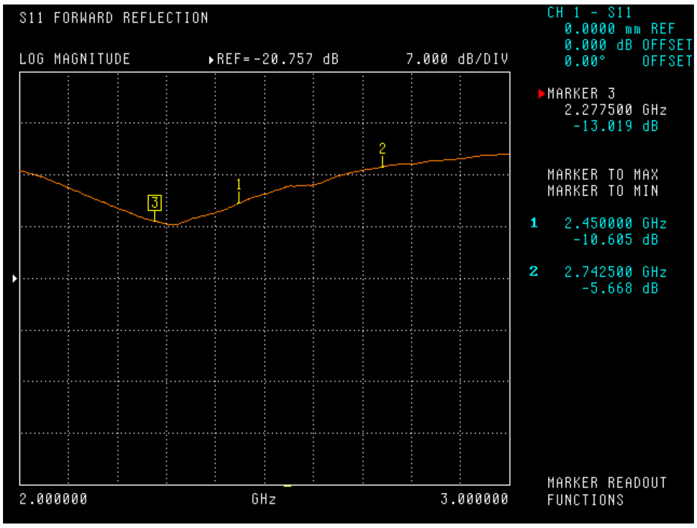


Figure 48. S11 of meandered monopole antenna on TPU_U073, stretched over the x-axis, with Ink CI-1036, while stretched for 10% of its original length.

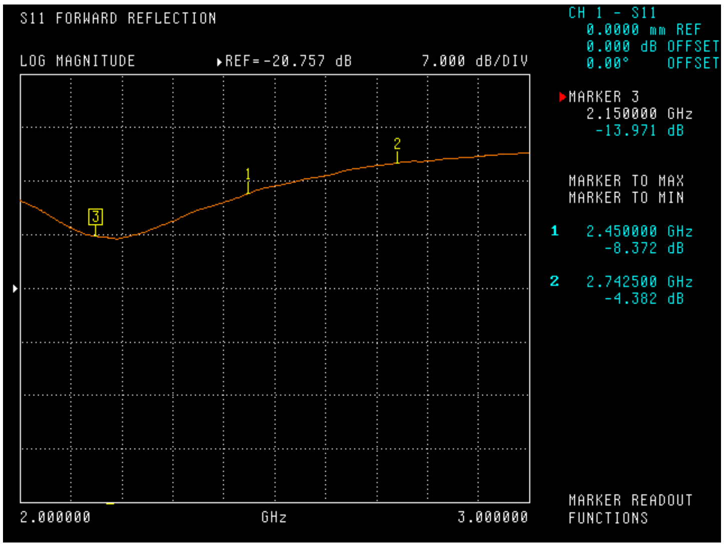


Figure 49. S11 of meandered monopole antenna on TPU_U073, stretched over the x-axis, with Ink CI-1036, while stretched for 20% of its original length.

4.3.2 Stretching over y-axis

In this section, I will report the measurement results of the meandered monopole antenna when it is stretched over the y-axis. The main difference between stretching over the y-axis over the x-axis is that the parameters that are stretched are different, however, it is expected that the results to be relatively close because of the symmetric nature of the geometry of the antenna itself. Table 9 shows the summary of the most important findings when the meandered monopole antenna was measured by stretching it over the y-axis at different stretching parameters. In this measurement section, I have reported a comparison between TPU_U073 and TPU_ID9211, and the results show comparable performance.

Table 9. summary of measurement results for meandered monopole antenna stretched over the y-axis

Figure	TPU substrate	Stretching Percentage	Frequencies	S11
Figure 50	U073	0%	2.45 GHz	-13.738 dB
Figure 51	ID9211		2.45 GHz	-12.468 dB
Figure 52	U073	5%	2.45 GHz	-17.257 dB
Figure 53	ID9211		2.45 GHz	-12.093 dB
Figure 54	U073	10%	2.45 GHz	-15.53 dB
Figure 55	ID9211		2.45 GHz	-12.95 dB
Figure 56	U073	20%	2.45 GHz	-16.763 dB
Figure 57	ID9211		2.43 GHz	-14.9 dB

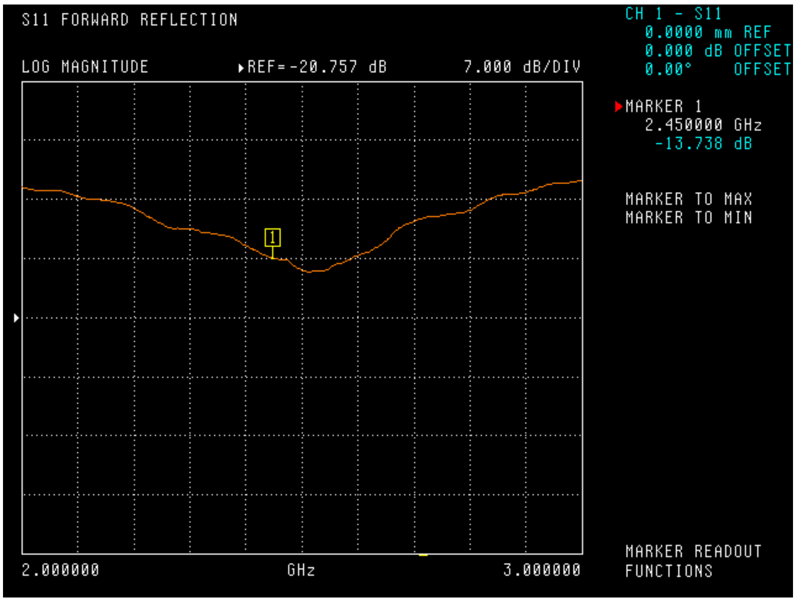


Figure 50. S11 of meandered monopole antenna on TPU_U073 stretched over the y-axis, with Ink CI-1036, while stretched for 0% of its original length.

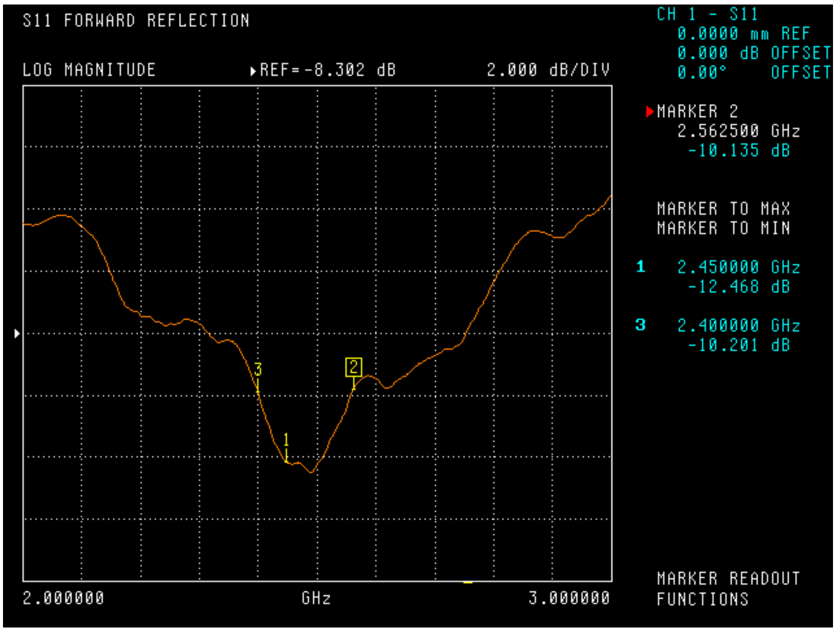


Figure 51. S11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis, with Ink CI-1036, while stretched for 0% of its original length.

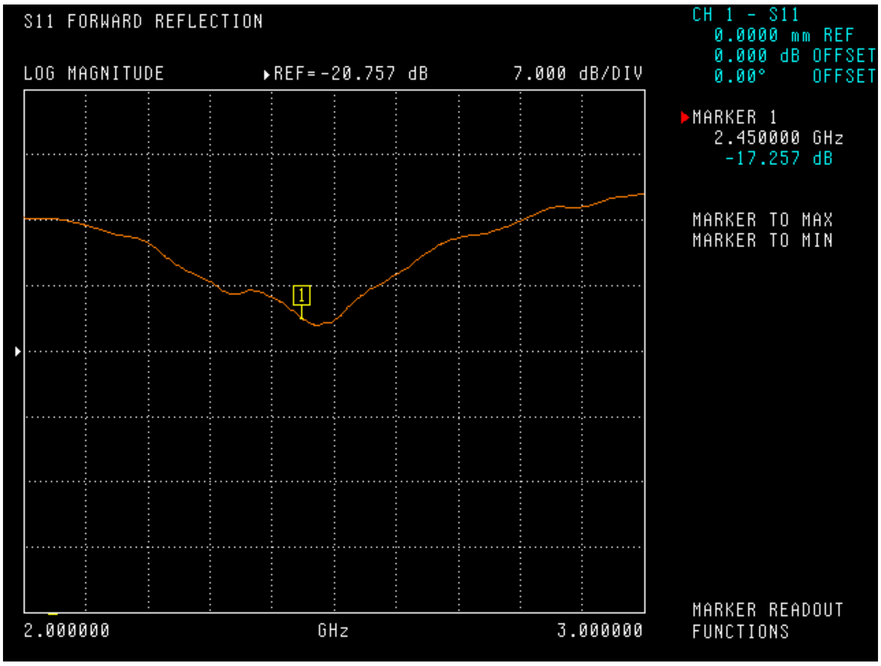


Figure 52. S11 of meandered monopole antenna on TPU_U073 stretched over the y-axis, with Ink CI-1036, while stretched for 5% of its original length.

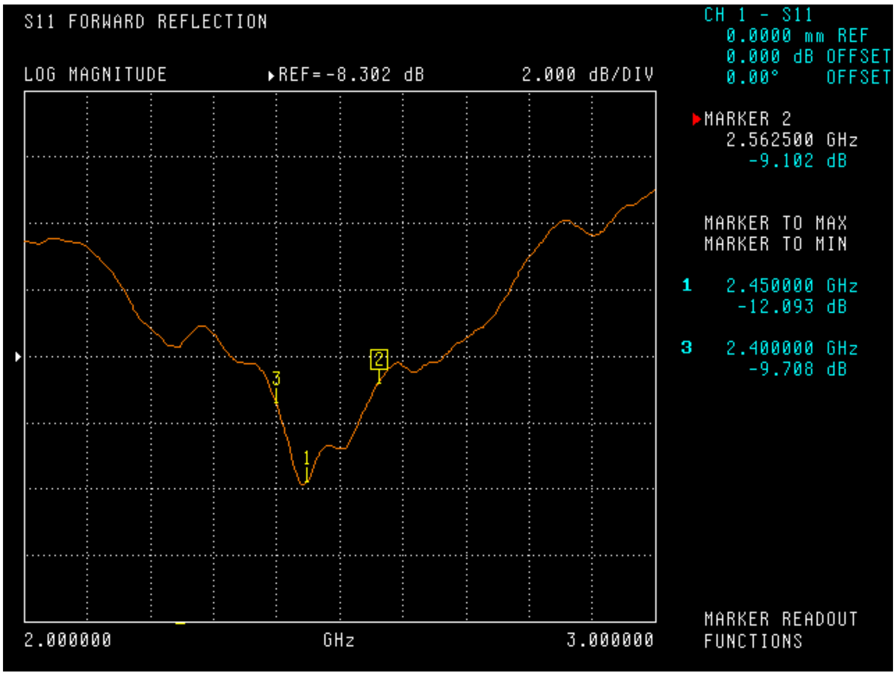


Figure 53. S11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis, with Ink CI-1036, while stretched for 5% of its original length.

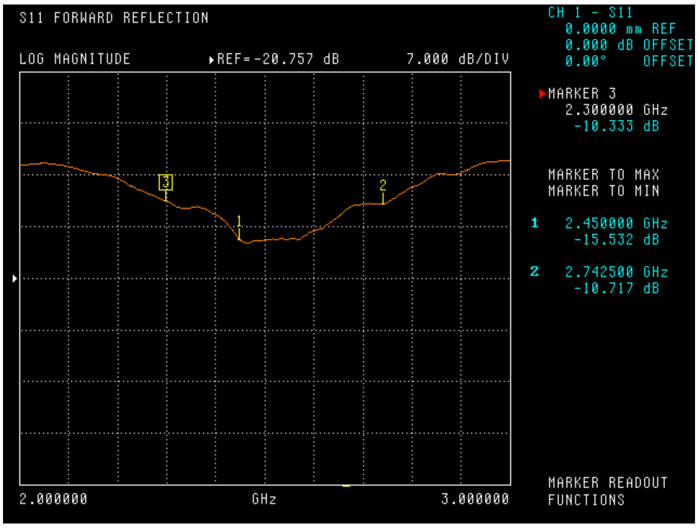


Figure 54. S11 of meandered monopole antenna on TPU_U073 stretched over the y-axis, with Ink CI-1036, while stretched for 10% of its original length.

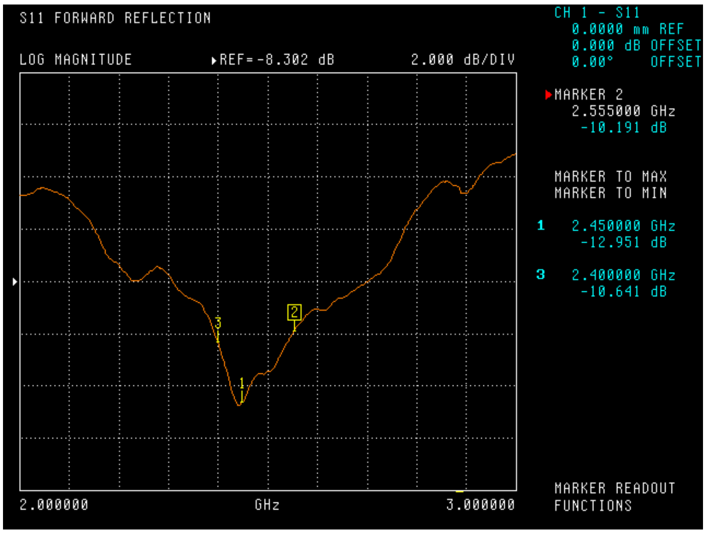


Figure 55. S11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis, with Ink CI-1036, while stretched for 10% of its original length.

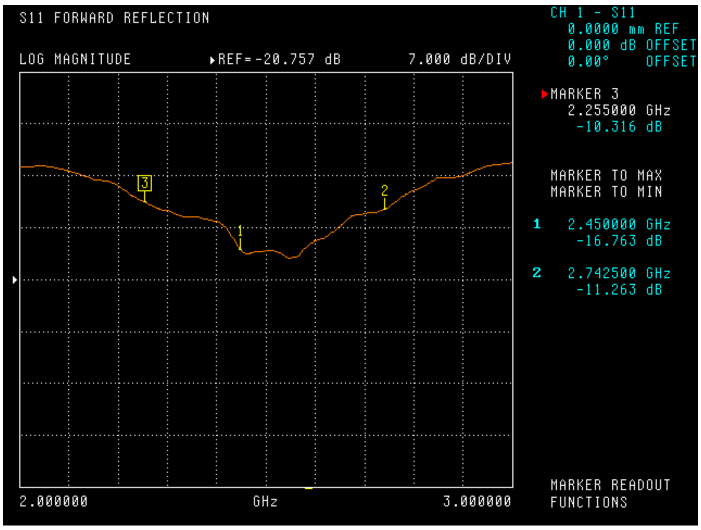


Figure 56. S11 of meandered monopole antenna on TPU_U073 stretched over the y-axis, with Ink CI-1036, while stretched for 20% of its original length.

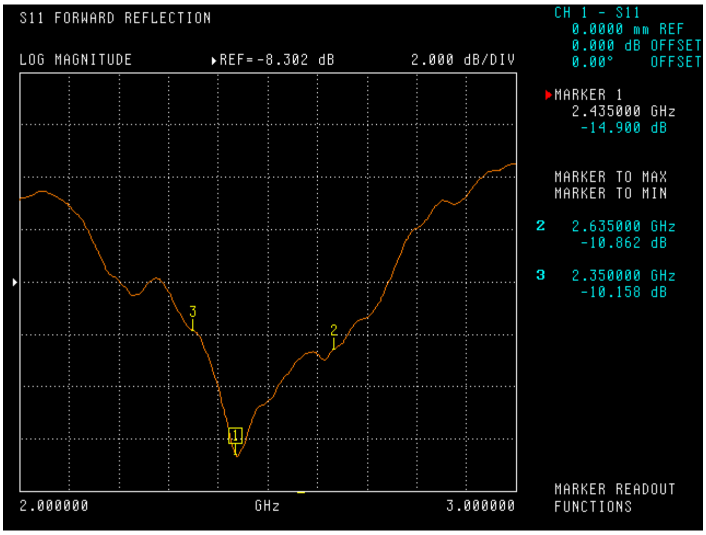


Figure 57. S11 of meandered monopole antenna on TPU_ID9122 stretched over the y-axis, with Ink CI-1036, while stretched for 20% of its original length.

To summarize, due to the geometry and the radiation principle of the meandered monopole antenna, it has shown multiple interesting properties that make it a very desirable antenna for TPU-based stretchable applications. For meandered monopole antenna, the gap and leg parameters can affect the meandered monopole antenna resonance frequency, hence the closer the values of these parameters are to each other, the more symmetric radiation response for the meandered monopole antenna when it is stretched over both of its axes. It is also clear from our simulations that there are no huge differences in the performance between TPU_U073 based antenna and TPU_ID9211 based antenna, yet there are minor differences that are mainly due to substrate thickness differences, instability of the measurement setup and the mechanical properties. Since TPU_ID9211 is thicker, therefore, it is relatively more mechanically stable.

Another interesting property we can notice is that the effect of stretching of the meandered monopole antenna is less compared to the same stretching percentage on the dipole antenna when it is stretched over its length. For instance, in Figure 22, it shows that the resonance frequency was pulled backward from 2.45 GHz to 2.23 GHz when the antenna is stretched up to 10% over its length, which corresponds to drop equals to 0.22 GHz, however, for meandered monopole antenna that utilizes the same TPU_U073 at Figure 33, the resonance frequency is reduced from 2.45 GHz down to 2.31 GHz for the same 10% stretching, which corresponds to drop equals to 0.14 GHz. This shows that the meandered monopole antenna is less sensitive to the stretching effect, with almost 63% over the dipole antenna when its stretched over its length. Hence, based on previous observation, the meandered monopole antenna shows much better performance if and only if it is known that the antenna will be stretched over its length only. However, the dipole has another unique property, that is when it is stretched over its width, the radiation performance of the dipole is almost constant. Hence, based on the stretchable dimension of the circuit or TPU, as well as its orientation of the antenna compared to that dimension, meandered monopole can be more desirable over the dipole or the other way around, more about the antenna orientation will come later in this chapter in the following chapter.

Finally, the measurements of the meandered monopole antenna show comparable results to the simulations, yet it is not very close to it. This is due to the very complex and unstable setup, as well as the mechanical properties of the antenna itself since the antenna was not properly supported when it is stretched and during the measurements. In addition, the reading can vary from one experiment to another for the same antenna, yet, the measurements show that the meandered monopole antenna can maintain its radiation performance to a very large extent as shown in Table 9.

5 OBSERVATIONS AND GUIDELINES

In this chapter, I will propose antenna selection and placement guidelines for engineers, in general, to show how to place a stretchable antenna on a stretchable substrate and provide clear steps for the monopole and dipole antennas in specific as they are very commonly used for the applications for which this thesis is conducted.

In order to evaluate the antennas in the scope of this thesis, I have put a criterion according to which an antenna would be categorized into a good or poor performing stretchable antenna. The most desirable stretchable antenna performance in our context is when an antenna performance is not drastically altered when stretched over any stretchable axis, yet it is still radiating regardless of the amount of stretching imposed. Also, the closer the resonance frequency of an antenna after stretching to the resonance frequency before stretching, the better and the more desirable the antenna is for stretchable applications. In addition to that, a good stretchable antenna would have a symmetric response when stretched regardless of the stretching model. Hence, a good stretchable antenna would show symmetric response when stretched over the x-axis, y-axis, or both. It is not easy to have all the above criteria fulfilled when utilizing 2D antennas that were not originally designed to be stretchable and to maintain performance when geometric deformation occurs to it. Hence, the closer the antenna response to the above-mentioned criteria, the more desirable the antenna.

The antennas that I am covering in the scope of this thesis are 2D antennas when such antennas are stretched, the change in the dimensions of the antenna causes a change in its performance. Specialists select a specific antenna for certain applications according to many parameters, including the available physical space, bandwidth, and other system-related parameters. For stretchable applications, in addition to that selection criteria, there are other parameters that can affect the antenna selection. To further explain, the microstrip patch antenna will be discussed as an example, and then I will set a general rule to make the selection criteria easier. Consider microstrip patch antennas that can come in multiple shapes, a rectangular patch antenna, for instance, that can have three different shapes, as in Figure 58.

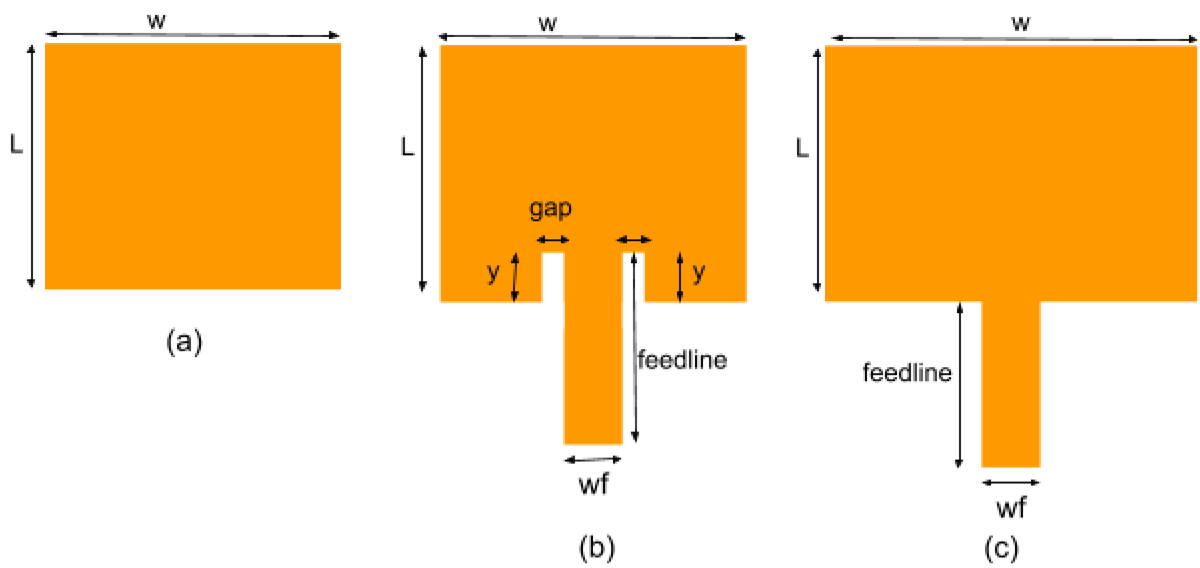


Figure 58. Possible structures for microstrip patch antenna.

Even though it is the same antenna type in Figure 58 (a,b,c), patch antennas, however, stretching over width will have a different response on each of the above antennas. Each of the above antennas has different parameters that will cause a different effect when stretched. In addition, different feeding methods and geometry have different effects on the response of the antenna when it is stretched.

In Figure 58 (a), stretching over *w* will affect the parameter *w* only, hence the patch antenna will have specific response change due to stretching. On the other hand, in Figure 58 (b), stretching over the same *w* will affect the parameters *w*, gap, and *wf*, this means the response due to the stretching over the same dimension *w* will have a completely different response when compared to Figure 58 (a).

Depending on the radiation theory of the antenna and the effect of each dimension on the radiation parameters of the antenna, one antenna design might be preferable over the other. However, in some cases, when an antenna has multiple design parameters that are directly related to its radiation properties, they could compensate for the effect of stretching on its radiation properties or cancel each other's stretching effect when the antenna is stretched similar to the case of the meandered monopole antenna. I conclude that antennas that have a smaller number of dimensions that affect its radiation parameters are more suitable for stretchable applications and easier to analyze and predict its performance when stretched.

Hence, a general guideline for a non-antenna specialist who needs to select a TPU-based antenna, select the antenna that has the least number of dimensions and yet satisfies the radiation properties that satisfy the application requirements.

In this study, I experimented and reported the effect of using different TPUs as a substrate for a stretchable antenna. According to the experiments and measurements which I have performed, TPU_U073 and TPU_ID9122 have different dielectric properties, hence, for the same antenna, each TPU has different values for the dimensions of the antenna. However, the antenna behavior when stretched with the same amount on both TPUs, have consistent behavior, so once the dimensioning of the antenna is calculated correctly, same stretching response for a specific antenna should be expected if the antenna is placed on either TPUs if and only if they have the same thickness. Also, I studied the effect of using different inks as the conduction layer for the printed antenna and how do different inks behave and affect the antenna radiation properties when stretched. The meandered monopole antenna measurements were done with different inks, and the results were the same regardless of the ink type. These results hold for our given bandwidth and operating frequency, which is around 2.45 GHz. Further research needs to be performed to study the effect of using different inks on stretchable antennas but on much higher frequencies.

In the scope of this thesis, I have studied microstrip patch antenna, dipole antenna, and meandered monopole antenna. I didn’t report any results related to patch antenna because the application requirements were that the substrate thickness is maximum 150µm, due to the nature of the microstrip and its radiation principle, microstrip didn’t behave as an antenna, rather it was just a poor radiator, hence, no patch antenna results are reported in this thesis.

Depending on the application, a specific antenna can be more suitable than another for many reasons, however, if I will give a general suggestion regardless of the application, I suggest the meandered monopole antenna to be used. The reason for that is meandered monopole antenna exhibits the best stretchable performance according to the definition that is stated at the beginning of the chapter, that the meandered monopole antenna has symmetric response when it is stretched over x-axis or y-axis.

Meandered monopole antennas exhibit the best performance because it shows symmetric behavior when stretched over the x-axis or y-axis. The reason behind that is the effect of stretching each design parameter on the overall antenna performance, as explained in Table 2, that the design parameters partially compensate each other’s effect, making the resonance frequency more stable.

To explain this further, I will provide a simple example; in Figure 8, assuming stretching on the y-axis, this will cause the width of segments that are parallel to the y-axis to increase, gap to increase and El – which is the substrate where the antenna is placed – to increase as well. According to Table 2, this will cause change on the resonance frequency to be increased due to the increase in *w*, but also decrease due to the increase of gap and El, in total, the resonance frequency will be reduced, but due to the compensation of *w*, the stretching effect is relatively acceptable.

The meandered monopole antenna exhibits the same stretching effect regardless which stretching axis is x-axis or y-axis, this depends as well on the relative dimensions of the leg and gap parameter, so if the meandered monopole antenna has symmetric design parameters where leg is equal to gap the response of x-axis and y-axis will be relatively close.

So far, I have discussed the effect of stretching an antenna on its radiation properties, however, the placement and orientation of an antenna on the TPU substrate or any other stretchable substrate can also affect the antenna radiation properties when it is stretched. It can also constrain the radiation properties to a certain desired behavior so that it is more suitable for the application under development. In addition, the undesired effect of stretching can be limited to a certain extent depending on the antenna orientation on the substrate. Hence, I have developed guidelines that will help engineers when placing the antenna on a stretchable substrate. The goal of the guidelines is to help the engineer place the antenna in a way that makes the radiation properties of the antenna least affected by stretching. In the scope of this thesis, the antenna placement and guidelines that will be provided will be mainly related to the dipole and monopole antennas. Other antenna structures will be further studied and published in the following publications.

Before discussing the guidelines, I have developed some novel terms that will help to explain some behaviors and introducing new terms that, as far as I know, were not introduced before.

- Antenna's critical dimension L_c: is the most sensitive and dominant antenna dimension that can affect the radiation parameters of the antenna if it is slightly changed. For example, in the case of a dipole antenna, L_c will correspond to the length of the dipole. It is usually calculated when $\theta = 0$ where θ is the angle between the length vector and the stretchable axis. Its value corresponds to the maximum acceptable value for that given dimension so that the antenna performance is still acceptable.
- Critical stretching percentage S_{pc}: the maximum allowed stretching percentage for the substrate so that the antenna can still radiate within the system requirements when the antenna's L_c dimension has an angle θ with the stretching axis, where $0° \leq \theta \leq 90°$.
- Critical angle θ_c: the minimum angle θ between the substrate's stretching axis and the antenna's critical dimension L_c so that the antenna is still radiating within the system requirements when the substrate is stretched to its maximum percentage. It is always the case that $0° \leq \theta_c \leq 90°$.

Antenna placement and orientation guidelines will be divided into two scenarios, when it is known that the TPU will be stretched over one axis only, and when the TPU is stretched over x and y-axis.

5.1 TPU stretched over a single axis

The first case is when the TPU is stretched over single access. In order to give a general view of the antenna orientation possibilities on TPU, I will give a quick example of a dipole antenna. Assuming a TPU substrate that is rectangular and has a length of $L_s = 20mm$, and width of $W_s = 60mm$. Dipole antenna with length $L = 10mm$ and width $W = 0.8mm$. It is also assumed that the substrate can be stretched up to 50% of its original value. It is also assumed that the TPU is stretchable only over L_s dimensions. There are three possibilities to place the dipole antenna on the TPU, as shown in Figure 59.

First possibility when the dipole is parallel to L_s. When the TPU is stretched up to 50% along the L_s dimension, it means that L_s will be 30mm instead of 20mm, and L will be 15mm instead of 10mm. In this case, the resonance frequency will be significantly pulled backward based on which substrate is used and its dielectric properties. When the dipole's L is parallel to L_s, this cases the biggest possible effect on the antenna performance, since θ, in this case, is zero, which means that the dipole length will be affected by the same percentage as the stretching of the TPU itself that means if the substrate is stretched up to 50% of its original length, the dipole length as well will be stretched by 50% of its original length.

Second possibility when the Dipole perpendicular to L_s. When the TPU is stretched up to 50% along the L_s dimension, it means that L_s will be 30mm instead of 20mm, but L remains the same as its initial value, which means that the resonance frequency, in this case, doesn't change under stretching. This is a very desirable behavior and should always be the goal when deciding the orientation of the antenna on the TPU. The explanation for this scenario is that since θ, in this case, is 90°, which means that the dipole length will not be affected by the stretching of the TPU, as stated in equation (9).

Finally, the last possibility for placing the dipole on a stretchable TPU is when the dipole has an angle θ with the stretchable dimension of the TPU substrate. In this case, when the TPU is stretched up to 50% along the L_s dimension, it means that L_s will be 30mm instead of 20mm, but the effective change on the dipole length will depend on cos (θ) that the dipole is making with L_s. The first and second scenarios are special cases from this scenario where θ is 0° and 90°, respectively.

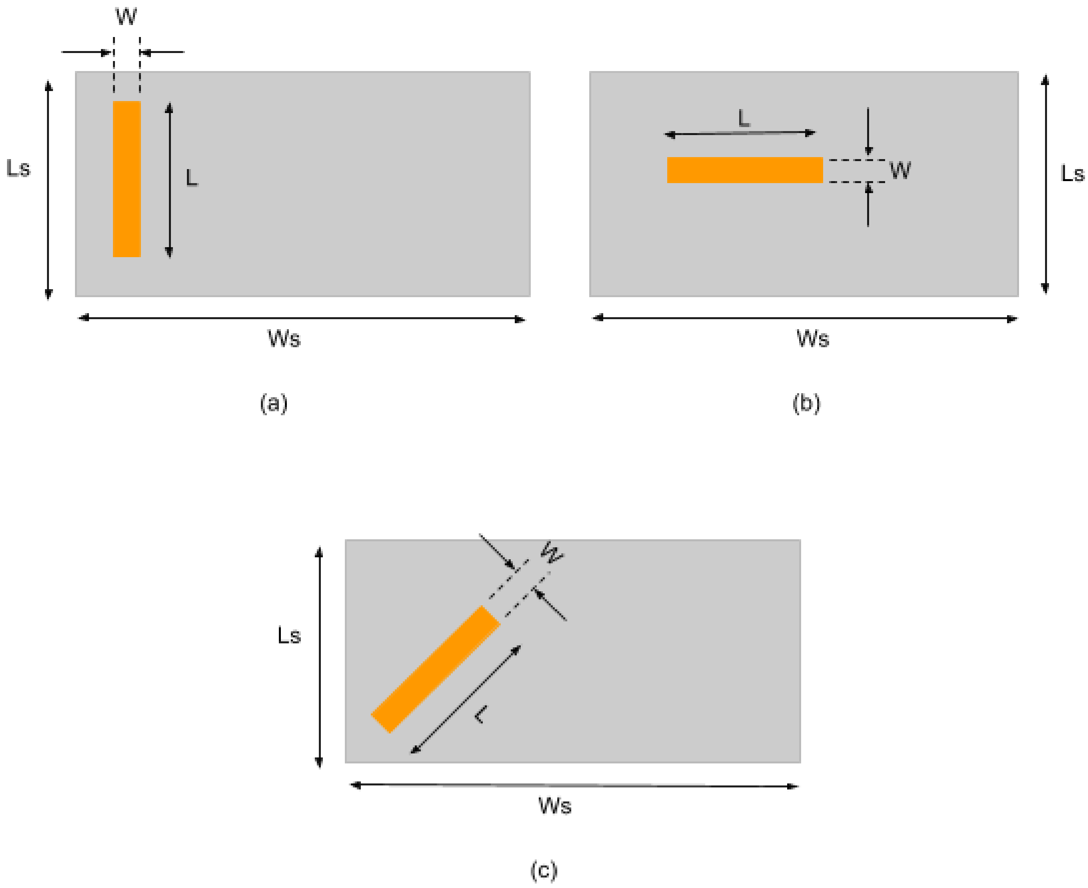


Figure 59. Dipole antenna orientation options on a TPU when the TPU is stretched over a single dimension.

It is a valid argument due to practical reasons to assume that the TPU substrate will be stretched in a specific axis only and not expected to be stretched over other axes. In this case, Figure 60 explains the steps which should be followed in order to have a minimal stretching effect on the antenna radiation properties. These steps are also explained in more details in a clear, and ordered steps as following

1. Calculate L_c for $\theta = 0$, it simply means calculate the value for this dimension simply as the theory states.

2. Check if the maximum stretchability percentage of the TPU substrate can cause L (in this case the length of the dipole) to be greater than L_c when L is parallel to L_s, where L_s is the stretchable dimension of the TPU substrate. If this does not occur, then the antenna can be placed in any orientation on the TPU substrate. If $L > L_c$, then move to the next step. To perform that check, calculate the new value for L after when the TPU is stretched to its maximum value as explained in equation (9), Where L_2 represents the new value of L when the substrate is stretched to its maximum value, L_1 is the original value of L before stretching, and $S\%$ is the maximum stretchability percentage of the TPU over the stretchable dimension of the TPU.

$$L_2 = [L_1 * S\% * \cos(\theta)] + L_1 \tag{9}$$

3. Calculate θ_c according to equation (10), if θ_c is not defined, then select a different antenna. If no other antenna can be utilized for any practical reasons, then define S_{pc} for that given application

$$\theta_c = \cos^{-1}\left(\frac{L_2 - L_1}{L_1 * S\%}\right) \tag{10}$$

4. If θ_c exist, then the antenna can be placed with any angle θ, where $\theta_c \leq \theta \leq 90°$. Usually, 90° degrees should be the ultimate goal, because when L_c is perpendicular to the stretching axis, it means it is independent of the stretching, and its value will not be altered. Hence the antenna radiation performance will not be affected. However, in some applications, angles less than 90° can be useful, since it can add extra usability of the antenna to be used as a feedback loop on the stretchability percentage of the circuit in real-time, this will be discussed in more details later in this chapter.

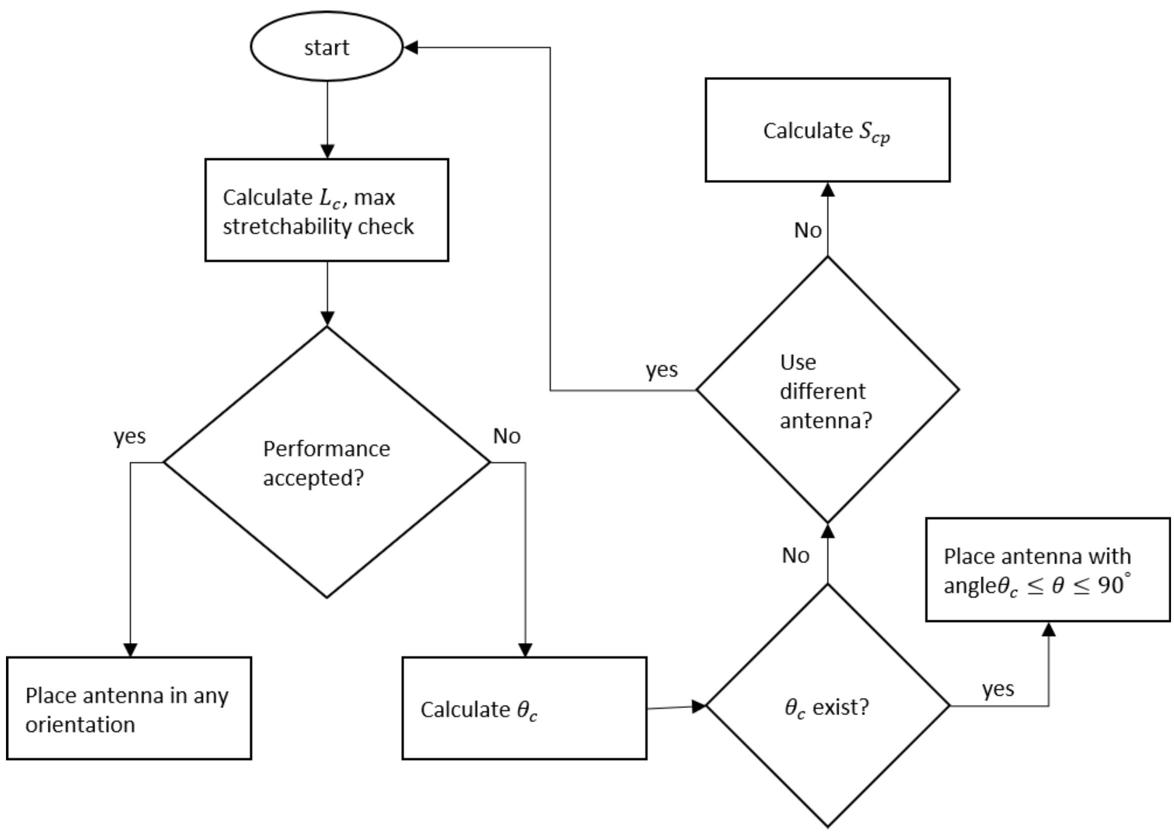


Figure 60. Antenna placement guidelines when TPU is stretched over only one axis.

5.2 TPU stretched over x-axis and y-axis

In the first case, I assumed that the TPU substrate would be stretched over a single dimension. However, it is possible that the TPU substrate can be stretchable over x and y dimensions as well. Hence, I have presented detailed guidelines and flowchart in Figure 61 concerning this scenario. In this algorithm, I assume that both TPU's stretchable axis can be stretched to the same amount. So $S\%$ is the same for x-axis and y-axis.

1. Calculate L_c for $\theta = 0$, it simply means calculate the value for this dimension simply as the theory states.
2. For each dimension, check if the maximum stretchability percentage of the TPU substrate can cause L (in this case the length of the dipole) to be greater than L_c when L is parallel to L_s, where L_s is the stretchable dimension of the TPU substrate, calculations are done according to equation (9).
3. If stretching over both dimensions does not cause $L > L_c$, then the antenna can be placed in any orientation on the TPU substrate. however, placing the dipole's L_c perpendicular to the dimension that has the most probability of stretching will give the best performance because it means that most of the time, the antenna will suffer of least stretchability effect on its performance.
4. If stretching the TPU causes $L > L_c$, then calculate θ_c using equation (10).
5. If θ_c is not defined, then select a different antenna. If no other antenna can be utilized for any practical reasons, then define S_{pc} for that given application.
6. If $\theta_c \geq 45°$, then the antenna should have an angle $\theta = \theta_c$ with the least probable stretching direction, or as close to θ_c as possible.
7. If $\theta_c < 45°$, then the antenna should have an angle θ where $\theta_c \leq \theta \leq 90° - \theta_c$. Where θ is the angle between the antenna's L_c and the least probable stretching axis of the TPU substrate.

As a general rule when deciding the orientation of the antenna on a TPU, is to minimize the effective change on the antenna parameter due to stretching, this effective change could be calculated for each antenna dimension that can be affected by stretching using equation (11) where ΔL is the effective change of a given antenna dimension L.

$$\Delta L = L * S\% * \cos(\theta) \tag{11}$$

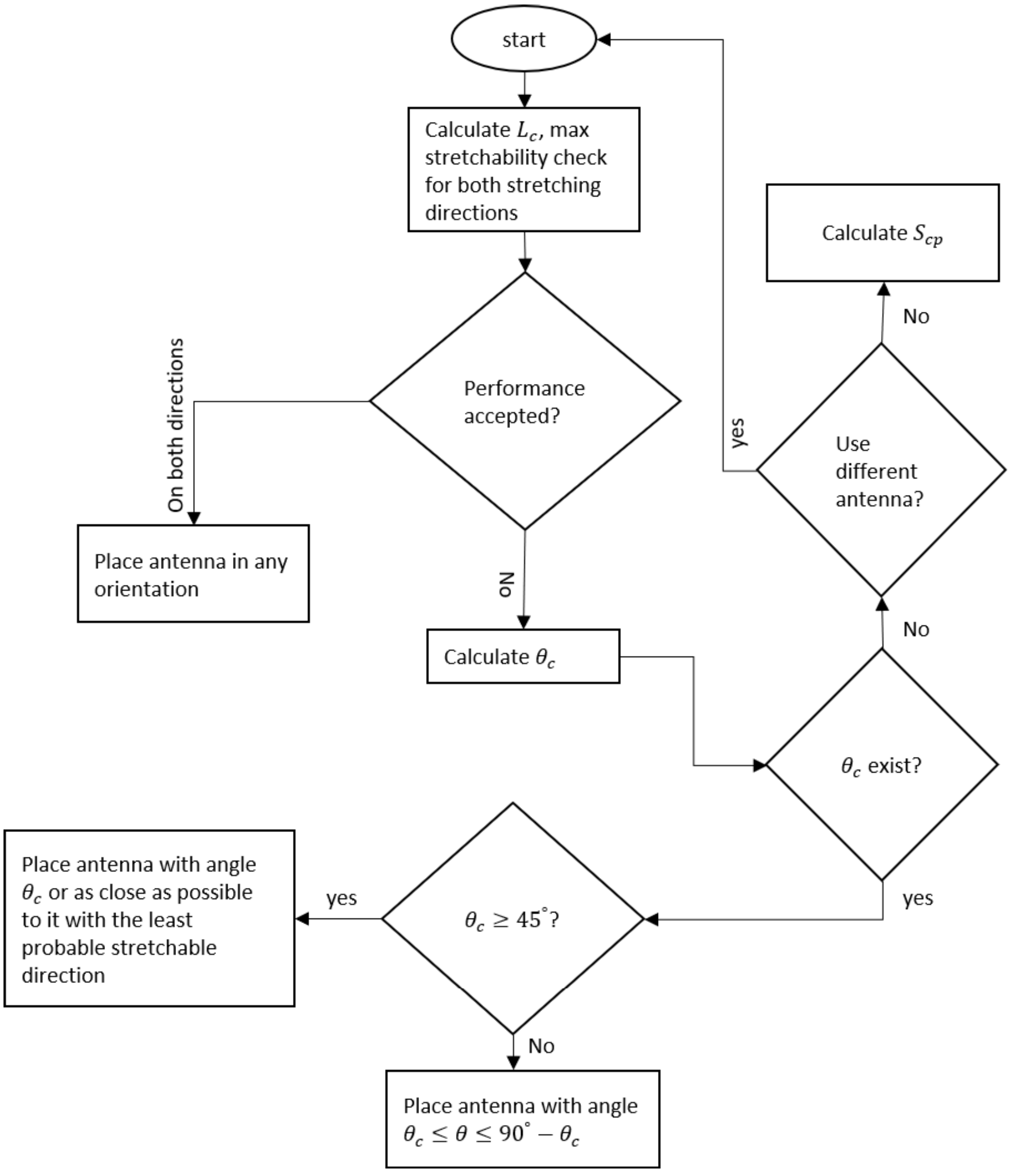


Figure 61. Antenna placement guidelines when TPU is stretched over both axes.

6 SUMMARY

In conclusion, the main objective of the thesis was to study the effect of stretching on different antenna structures. I have simulated a patch antenna, a dipole antenna, and a meandered monopole antenna, however, I did not report the results of the patch antenna, since the performance was not acceptable at all when it is used on 100µm thick TPU. Also, I did not manufacture the dipole because of the complexity of its feeding setup while taking into consideration the complexity of the setup for the stretchable measurements itself. Hence, only the meandered monopole antenna was measured with a VNA. Based on the simulation results as well as the measurements, I reported important insights and guidelines when using a 2D antenna on a stretchable substrate. I also found that the orientation of the antenna, the probability of stretching the TPU substrate over different axes, and the available antenna types are very important parameters that will eventually determine the quality of the performance of the stretchable antenna in any given application. It is advisable that the exact and final shape of the stretchable circuit containing the 3D component design be available before starting to implement the antenna placement guidelines mentioned in the previous chapter. Also, the probability of stretching different axes of the TPU substrate should be available beforehand, in case it is not possible to know it, assume equal probability.

Wire monopole, dipole, and meandered monopole antenna have shown acceptable performance utilizing both TPUs, which are TPU_U073 and TPU_ID9211. However, TPU_ID9211 has shown better stability in measurements, and this can be referred to as its thicker sample, which was 150µm that made it a bit more rigid compared to TPU_U073. I have not seen any differences in the performance of the antennas when utilizing different inks, hence it is left to the application engineer to select which ink to utilize according to different parameters not related to the antenna performance. The dipole antenna is not advised to be utilized since it is normally more complex to feed than the wire monopole and the meandered monopole. Depending on the application, wire monopole or meandered monopole antenna can be selected, if it is clear that stretchability will occur only in one dimension, then wire monopole can be a good choice only if it’s possible to have it perpendicular to the stretchable axis. If it is equally expected that both axes will be stretched, then the meandered monopole antenna has shown quite stable, consistent, and semi-symmetric response to stretching over its either axis.

Future work

In this thesis, I have simulated dipole antenna and meandered monopole antenna for the use of stretchable TPU with a standard thickness of 100µm to 150µm at Bluetooth frequency of 2.45 GHz. There are lots of future studies to be done concerning the utilization of 2D antennas on stretchable TPUs. As well as further characterization of TPUs and stretchable inks for RF applications at much higher frequencies as well as sub-THz frequencies and study the effect of stretching the substrate and the ink on the antenna performance and compare that to the performance of the antenna on stretchable TPU at much lower frequencies. Also, it might be useful to study the effect of different processing parameters of the TPU and inks when they are manufactured on the antenna performance when the TPU is stretched. In addition to the study on the TPU itself, other antenna structures need to be simulated and modeled to be used on stretchable TPUs. In this study, dipole, monopole, and meandered monopole antennas were the core of the study, however other types of antennas should be investigated to enrich the available options that to be utilized on TPUs for stretchable applications.

Even though 2D antennas were not designed to be stretched while maintaining its performance, there are lots of applications that can benefit from this commonly considered undesirable behavior of an antenna. The fact that the antenna can change its radiation parameters when stretched can be utilized as a feedback signal that if processed properly, it can have indications of mechanical and physical change of the circuit that contains the antenna, hence the antenna, in this case, can be utilized as a sensor for physical change of the dimensions of the circuit. Another application that can benefit from the fact that if the physical dimensions of the printed antenna are changed, it will change its radiation properties, including its resonance frequencies, is using the antenna as a multiband antenna that can be tuned by controlling the stretching percentage of the containing TPU substrate. Although this kind of application can have its own challenges, it is very interesting challenges to be investigated further specifically when the substrate is TPU-based.

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8 APPENDICES

Appendix 1 Matlab code to design meandered monopole antenna layout

Appendix 2 Matlab code to calculate the exact dimensions of patch antenna

Appendix 1 Matlab code to design meandered monopole antenna layout

In this Appendix, I will provide a Matlab code that I have developed in order to generate the exact x and y locations as shown in Figure 62 to easily design the layout of a monopole antenna for PCB design.

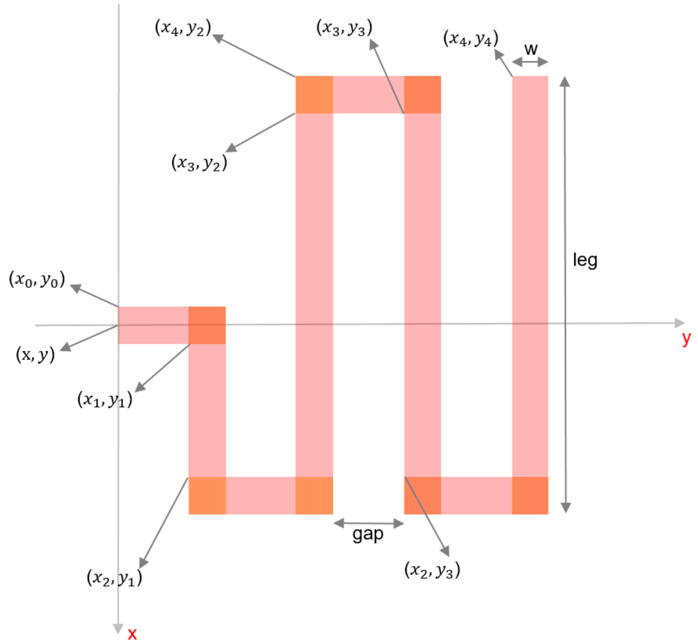

Figure 62. Meandered Monopole Antenna Design Guidelines

```
function coordinates = GenMeanderedMonopoleAntennaCoord(Xorigin,Yorigin,w, leg, gap)

    widthofYSegment =   w;
    widthofXSegment =   w;
    x0              =   Xorigin - (widthofYSegment/2);
    y0              =   Yorigin;
    coordinates     =   [x0 y0];
    x1              =   Xorigin+0.5*widthofYSegment;
    y1              =   y0+gap;
    coordinates     =   [coordinates;x1 y1];
    x2              =   Xorigin - widthofYSegment - (0.5*leg);
    y2              =   (2*gap) + widthofXSegment;

    coordinates     =   [coordinates;x2 y2];
    x3              =   Xorigin+widthofYSegment-(0.5*leg);
    y3              =   (3*gap)+(2*widthofXSegment)+y0;
    coordinates     =   [coordinates;x3 y3];
    x4              =   Xorigin-(0.5*leg);
    y4              =   (4*gap)+(3*widthofXSegment)+y0;
    coordinates     =   [coordinates;x4 y4];

end
```

Appendix 2 Matlab code to calculate the exact dimensions of patch antenna

In this Appendix I provide my own Matlab code which I used to quickly calculate the dimensions of the microstrip patch antenna based on h, perm, for which are the height of the given substrate, permittivity of the substrate and the resonance frequency where the antenna is expected to resonate

```
function [width,l,delta_l,effective_perm, effective_length,yo] = CalcDim(h,perm,fo)
%frequecny is entered in Hz
%h is entered in cm

Vo = 3e8; % in m/s
width              =   ((Vo/ (2*fo) ) * sqrt(2/ (perm + 1) ))*100; %results are in cm

effective_perm     =   ((perm+1)/2) + ( ( (perm-1)/2 )* ((1+ (12*(h/width)) )^(-0.5)) );
delta_l_numerator  =   (effective_perm + 0.3)* ( (width/h) +0.264 );
delta_l_denumerator =  (effective_perm - 0.258)* ( (width/h) +0.8 );
delta_l            =   (0.412*h)* (delta_l_numerator/delta_l_denumerator ); % result in cm

l                  =   ((Vo/ (2*fo*sqrt(effective_perm)) )*100) - (2*delta_l); % we multiplied by 
100 to convert from m to cm since delta_l is in cm
effective_length   =   l + (2*delta_l);

lambda0            =   (Vo*100)/fo;
Ko                 =   (2*pi)/lambda0;
x                  =   Ko*width;

I                  =   2 + cos(x) + x*sin(x) + (sin(x)/x);
G1                 =   I/(120*(pi^2));

Rin                =   1/(2*G1);
yo                 =   (l/pi) * acos( sqrt(50/Rin) );

end
```